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THE USE OF FIBRE REINFORCED CONCRETE FOR HIGHWAY REHABILITATION

presented by

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SYNOPSIS

During the fall of 1984, a field test on full depth fibre-reinforced concrete slabs was done in the Montreal area, during repair work on Highway A-15. Both steel and polypropylene fibres were used.

The homegeneity and reproductibility of the dispersion of the fibres were carefully checked during the concreting.

The properties of the fibre-reinforced concrete were investigated: compressive and tensile strength, flexural and fatigue resistance, abrasion, impact shrinkage and corrosion.

Joint meters were set in sawed and construction joints to monitor the effect of temperature on slab length.

The main findings of this research program are:

1: It is better to add steel fibres at the concrete plant rather than at the job site.
2: There is no abnormal slump and air loss during transportation (1 hour)
3: Compressive strength is increased.
4: The 7d module of rupture of fibre reinforced concrete is higher than the 28d strength of the plain concrete.

5: Fibre-reinforced concrete exhibits the same shrinkage as plain concrete.

6: The sawed joints did not open during the first six months; all the displacements were transfered to the construction joints (spacing 60 ft.) for the steel fibre reinforced concrete.

7: There was no advantage to add polypropylene fibres in concrete used to repair highway slabs.

8: 48 kg/m^3 (81 pounds/c.y.) of steel fibres reinforced too much the fatigue strength of concrete for highway repairs.

I - RESEARCH OBJECTIVES

The making of experimental slabs with fibre reinforced concrete on highway A-15 had the following objectives.

1: To master polypropylene and steel fibre reinforced concrete (mix design, batching, transport and pouring)

2: To caracterize the properties of fresh and hardened fibre-concrete (entrained air, workability, shrinkage compressive and flexural strength, modulus of elasticity, fatigue and impact resistance and corrosion, etc...)

3: To verify the behaviour of in situ fibre-concrete from cores and joint meters placed in sawed and construction joints.

4: To study the economical aspect of fibre reinforced concrete for repairs or reconstruction.

5: To make recommendations on the possibility of using fibre-concrete for repairs or reconstruction.

CONCLUSIONS

1: Although fibre manufacturers (polypropylene, steel) suggest adding fibres at the job site, this would result in unsatisfactory dispersion. This procedure delays considerably the work at the jobsite, and it has been found very difficult, not to say impossible, to obtain an homogeneous dispersion of the fibres which tend to produce some balling.

2: The fibres must be added at the batch plant.

3: For steel fibres, mix design should be modified so that fine and coarse aggregates are in equal proportions.

4: When 50 mm steel fibres are added, it is preferable to use 14 mm maximum size diameter rather than 20 mm.

5: There is no loss of slump or entrained air during transportation when fibres are added at the batch plant.

6: A remarquable homogeneity of dispersion of the fibres are attained which can be reproduced when they are added at the batch plant.

7: The drying shrinkage of the concrete is not modified by the addition of polypropylene or steel fibres.

8: The modulus of elasticity does not change significantly by the addition of fibres.

9: The compressive strength for 100 X 200 mm cylinders is generally 15% higher than that measured on 150 X 300 mm cylinders.

10: Steel fibres increase very significantly the splitting tensile strength of concrete at 28 days and even more at 7 days. At 28 days, the tensile strength is increased by 55% and by 92% at 7 days. The 7/28 ratio for steel fibre reinforced concrete is .92 and .85 for plain concrete so that the tensile strength of steel fibre reinforced concrete at 7 days exceeds by 42% the tensile strength of plain concrete at 28 days.

11: Polypropylene fibres does not increase the tensile strength of concrete.

12: The addition of steel fibres increases very significantly the ductile behaviour of the composite after first crack.

13: The addition of polypropylene fibres does not improve the behaviour of the concrete after first crack; the fibres stretch as the crack widens.

14: For fatigue endurance, the use of steel fibres dramatically improves this property. The effectiveness of the fibres are mostly felt in this field.

15: The controlled deflection caracteristics of the steel fibres reinforced concrete were improved after ten million fatigue loadings.

16: Precision in measuring the impact resistance of fibre reinforced concrete is very difficult. However the addition of fibres into concrete improves greatly this property. The use of steel fibres gives far better results than polypropylene fibres.

17: The abrasion resistance of concrete is not modified significantly by the use of steel or polypropylene fibres. Decreasing maximum aggregate size and increasing sand content cancels the gains drawn by the presence of the fibres.

18: Steel fibres exposed to a de-icing salt corrode rapidly. The damaging effect is limited to the exposed fibres.

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1 - EXPERIMENTAL SLAB IDENTIFICATION AND PHYSICAL CHARACTERISTICS

Figure 1 shows the experimental slab location and the type of concrete which was used during the construction. Table 1 shows their physical characteristics including:

- type of concrete
- slab thickness
- joint spacing
- joint depth
- whether dowelled or sawed joints

2 - CODIFICATION OF CONCRETE MIX DESIGN

To ease the text comprehension, code numbers have been assigned to the different concrete mixes as follows:

SITE OF SAMPLING	MIX DESIGN #	TYPE OF CONCRETE POURED	BEFORE OR AFTER FIBRE ADDITION	LOAD NUMBER
P = PLANT NOTHING = JOB	1 TO 6	AC = STEEL FIBRES PP = POLYPROPYLENE FIBRES OR = PLAIN CONCRETE	F = AFTER NOTHING = BEFORE	

EXAMPLE 1) P5 ACF-2

P = concrete sampled at batching plant
5 = concrete mix # 5
AC = concrete poured with steel fibres
F = concrete sampled with the fibres
2 = sampling in second load

EXAMPLE 2) 5 AC-2

nothing = concrete sampled at job site
5 = concrete mix #5
AC = concrete poured with steel fibres
nothing = concrete sampled without the fibres
2 = sampling in second load

3 - MATERIALS

Table 2 shows the physical characteristics of the materials used for the manufacturing of concrete and table 3 shows the typical gradation for fine and coarse aggregates and the different coarse aggregate fractions used for the different types of concrete mixes.

The steel fibres used were the Dramix™ ZP 50/.50. These fibres are sticked together with a water soluble glue and are dispersed easily into concrete.

The polypropylene fibres were Fibremesh™, 2 inches long.

Concrete was supplied by Demix Béton of Longueuil.

NOTE: Steel fibres are generally characterized by their aspect ratio = l/d (l = length, d = diameter) which was 100 in our case.

4 - SAMPLING OF CONCRETE

4.1 SAMPLING PROGRAM

Concrete was sampled in three different ways:

1) Complete sampling of fresh concrete
2) Control sampling of fresh concrete
3) Coring of hardened concrete

The number and distribution of samples taken are shown on tables 4, 5 and 6. Table 7 shows the number of controls and complete sampling and their identification for each of the three days.

4.2 SAMPLING MATERIAL

The following material was used to mould fresh concrete samples:

1) 100 x 200 cylinders : ABS pipe made by University of Sherbrooke.
2) 150 x 300 cylinders: standard thin or thick wall cylinders.
3) 100 x 100 x 400 beams: made of PVC sheet by University of Sherbrooke. (flexure)
4) 100 x 100 x 375 beams: steel mould made by University of Sherbrooke. (shrinkage)
5) 76 x 76 x 356 beams: steel mould (corrosion)

4.3 CONCRETE SAMPLING

The concrete samples taken at the job site before the addition of the steel or polypropylene fibres were made from the concrete that was first unloaded from the mixer truck.

However the sampling of plain or fibre concrete, was done in two different ways according to the days of sampling.

1) For the first day, samples were made from the first concrete unloaded after the fibre addition.
2) For the second and third day, samples were taken after unloading 2 m^3 of concrete.

The latest provides more representative concrete samples.

4.4 CONCRETE SAMPLES

4.4.1 CONSOLIDATION OF SAMPLES

Since fibre concrete is less easy to handle than plain concrete and was poured with a low slump, all samples were consolidated using two vibrating tables. All the concrete samples were consolidated the same way.

To prevent the scatter in the results, all samples for a given test were consolidated on the same vibrating table. For instance, all beams were vibrated on the first table and all cylinder moulds were vibrated on the other vibrating table.

4.4.2 INITIAL PROTECTION

Just after moulding, samples were covered with a polyethylene sheet and an insulating blanket. The minimum and maximum temperatures recorded during the first 24 hours are as follows.

	MAX.	MIN.
1) first day	28°C	18°C
2) second day	-	-
3) third day	23°C	14°C

4.4.3 CURING OF SAMPLES

All samples were cured in water immediately upon demoulding.

5. CONCRETE MIX DESIGN

The characteristics of each type of concrete is shown in Table 8. The concrete mix designs with steel fibres were suggested by the fibre manufacturer. Following laboratory trial mixes results and the fibre manufacturer's advice, it was agreed upon to use a fibre content of 48 kg/m^3 or 0.6% volume content, and to increase the sand proportion of the plain mix, in order to avoid dispersion problems of the fibres. Even more, we were advised to add the fibres at the job site by the same fibre manufacturer.

For laboratory mixed concrete, the addition of steel fibres causes no problems, because fibres are added slowly in small quantities and are spread over a large surface, thus producing an homogeneous mix without any balling. However, when fibres are added at the jobsite into the mixer truck, the homogeneity is not so obvious to attain, which has brought us to modify the method of fibre addition and the gradation of the coarse aggregate.

5.1 FIRST DAY SAMPLING (OCTOBER 18TH, 1984)

The concretes used for the first day are identified as mixes #1, #2 and #3. These concrete mix designs appear on table 9. In each case, the fibres were added at the jobsite, after adding some superplasticizer when the concrete was too stiff.

5.1.1 Mix #1

The first concrete had a coarse aggregate (c.a.) content of 985 kg/m^3 of which 465 kg was 20 mm c.a. After adding the fibres, we observed a number of defects.

1) the concrete appeared to be very harsh.
2) fibre balling occured in large quantities provoked by the fibres not penetrating enough throughout the mixer and causing an uneven dispersion.
3) fibre distribution was highly variable.

After this first test, it was decided to substitute 30 kg of 20 mm CA for the same weight of sand, to add the fibres in small quantities and mix thouroughly between each fibre addition.

5.1.2 Mix #2

Even after decreasing the quantity of c.a., adding the fibres many separate times and mixing thouroughly between each addition, we still obtained:

1) a harsh mix, but less than mix #1
2) fibre balling, but less than mix #1
3) uneven dispersion

Although the results obtained on the second test were less catastrophic than the first test, results were far from being acceptable.

For the third test, it was decided to substitute another 30 kg of c.a. and to increase the slump before adding the fibres.

5.1.3 Mix #3

Despite a 180 mm slump before adding the fibres, and 60 kg c.a. replacement, it had not given satisfactory results. It should be mentionned that the fibres were added very fast in order not to delay the construction site.

When the concrete was unloaded, these observations were made:

1) dramatic slump loss (from 180 to 40 mm)
2) a lesser fibre content as the mixer truck was unloading
3) fibre balling

Besides sampling mix #2 with steel fibres, it was also sampled before adding the fibres (complete test)

5.2 SECOND DAY SAMPLING (OCTOBER 23RD, 1984)

Steel and polypropylene fibre concretes and plain concrete were sampled.

5.2.1 Steel fibre concrete

The concretes used for the second day are identified as mixes #4 and #5. The mix designs are shown in table 9. The fibres were added at the batching plant.

5.2.1.1 Mix #4

Following the advice of Bekaert's technical representative, it was decided to use a ratio of c.a.: f.a. = 1:1 per volume using a 20 mm maximum size aggregate. Still the concrete contained very few balling fibres, but much less than the previous loads, and fibres were better dispersed in the concrete. Despite the changes, the concrete had a harsh appearance.

5.2.1.2 Mix #5

To improve the concrete's homogeneity, the 20 mm aggregate was removed from the mix, which led to a 20 kg/m^3 cement increase, and the c.a./f.a. ratio was maintained. Upon arrival at the job site, the concrete had a very satisfactory appearance:

- no balling
- very homogeneous
- good slump
- good entrained air
- easy pouring and surface finishing

It was decided to keep this same mix for the remaining pour.

5.2.2 Polypropylene fibre concrete

Polypropylene fibres were added to mix #6 which is in fact the concrete mix the contractor uses for highway construction. The fibre content was 1 kg/m^3. The following observations were made:

- the fibre dispersion was not quite uniform (some balling was produced)
- the addition of the polypropylene fibres did not seem to affect the workability.

5.2.3 Plain concrete

Mix #6 was the plain concrete specified for the job and was sampled as the reference concrete mix.

5.3 THIRD DAY SAMPLING (OCTOBER 25TH, 1984)

Only the steel fibre concrete was sampled on the third day. All sampled concrete was made using mix #5. The fibres were added at the batching plant. The concrete homogeneity was excellent. In fact, the fibre concretes were poured as easily and rapidly as the plain concrete poured on the second day. However, it would have been possible to increase slightly the 14 mm aggregate content.

CONCLUSION

The addition of steel fibres into mixer trucks is done with great difficulty. When fibres are added on top of the concrete they do not mix properly and hardly disperse through the mixer. The concrete becomes harsh at the top and prevents other additions of fibres to penetrate. When fibre content exceeds a certain critical volume, fibre balling occurs. The concrete on top, in the mixer, has a much higher fibre content than at the bottom of the mixer.

RECOMMENDATIONS

1°: When steel fibres are used in concrete, they must be added at the batching plant.

2°: The concrete mix design should be modified to provide a higher sand proportion.

3°: A 14 mm maximum size aggregate should be used to improve the concrete workability should the 20 mm aggregate be elongated and relatively coarse when using a fibre length of 50 mm with an aspect ratio of 100.

6 - RESULTS

The results for the discussion are shown on the following tables and figures.

A) Fresh concrete

Table 10 - Results of the first day sampling

Table 11 - Results of the second day sampling

Table 12 - Results of the third day sampling

Table 13 - Steel fibres volumetric fraction found in the mixed concrete

Figure 2 - Quantity of fibres in concrete when added at the job site or at the batching plant.

B) Hardened concrete

Table 10 - Results of the first day sampling

Table 11 - Results of the second day sampling

Table 12 - Results of the third day sampling

Table 13 - Steel fibres volumetric fraction found in the mixed concrete

Table 14 - Drying shrinkage of concrete cured for 7 days and 28 days in water

Table 15 - Modulus of elasticity of different types of concrete

Table 16 - Influence of cylinder size on compressive strength of concrete for the first day

Table 17 - Influence of cylinder size on compressive strength of concrete for the second day

Table 18 - Influence of cylinder size on compressive strength of concrete for the third day

Table 22 - Fatigue resistance of plain and fibre reinforced concrete at 28 days

Table 23 - Impact resistance of plain and fibre reinforced concrete

Figure 3 - Drying shrinkage of different types of concrete cured in water for 7 and 28 days

Figure 6 - Abrasion resistance at 48 days measured on cores taken from each types of concrete

Figure 7 - Steel fibre corrosion exposed to salt fog

Table 19 - Splitting tensile strength for different concrete samples

Table 20 - Flexural test results from 100 x 100 x 400 mm beams at one third loading

Table 21 - Percentage increase of fibre reinforced concrete over plain concrete

7 - DISCUSSION

Tests on fresh and hardened concrete were performed according to A.S.T.M. or C.S.A. standards of according to A.C.I.'s recommandations.

7.1 PROPERTIES OF THE FRESH CONCRETE

The fresh concrete characteristics for slump, air content and unit weight are shown on tables 10, 11 and 12 according to the day of sampling.

7.1.1 Slump

The slump was measured before and after the addition of fibres for the first day. These measurements show a great loss of slump due to the addition of the fibres. To compensate this loss of slump superplasticizer was added at the job site as shown in table 10.

The loss of slump was not measured on the second and third day, since the fibres were added at the batching plant. However, the slump behaviour was verified during the transport. Very little variations were noticed between the plant and the job although it took from 50 to 120 minutes for deliveries. It should be noticed that a small quantity of superplasticizer was needed to adjust the slump of a few loads (tables 11 and 12).

For polypropylene fibre concrete, there was also a significant loss of slump after the addition of fibres which was less than for the steel fibre concrete, but some superplasticizer was needed to compensate for the loss.

7.1.2 Temperature

The temperature of the concrete delivered at the job site for the three days was between 15 and 20°C. As a matter of fact, the climatic conditions were excellent during the three days of sampling.

7.1.3 Air content

7.1.3.1 Steel Fibre concrete

The air content was measured before and after the addition of steel fibres for the first day. It was noticed that the entrained air network is partially destroyed with the addition of steel fibres at the job. As it is shown in table 10, there is a 2 to 3% loss due to the addition of the steel fibres. However, some considerations should take into account that the air content was measured in the concrete that was first unloaded from the mixer truck.

When the fibres were added to the concrete at the batch plant, it was noticed that the air content was well maintained from the plant to the job site, when dispersion of the fibres was homogeneous (mix #5). Nevertheless, when fibre dispersion was not good (mix #4), a 3% drop in air was noticed.

In fact, for steel fibre concretes, good results were obtained, in regards of air content, with mix #5 only, where fibre dispersion was excellent. For all other mixes, there was some air loss during transportation.

7.1.3.2. Polypropylene fibre concrete

After addition of the polypropylene fibres there was an approximate 1% loss in air content.

7.1.3.3 Plain concrete

For the plain concrete, the air content was within the specification limits.

7.1.4 Unit weight

The unit weights for each of the sampled concrete are shown in tables 10, 11 and 12. The unit weight variation is a function of air and steel fibre content.

7.1.5 Homogeneity and dispersion of fibres

We have investigated a method for determining the dispersion homogeneity of the steel fibre in fresh concrete. Approximately, 4 kg of fresh concrete is taken and weighted at different intervals, at the beginning (B) at the middle (M) and at the end (E) of each load. The fine particles are then

washed away taking care not to loose any fibres. Then the remaining material is dried to constant weight, and steel fibres are picked up with a magnet. The fibre volumetric fraction can be calculated using the formula:

$$V_{fr} = \frac{P_f \cdot D_c}{P_c \cdot D_f} \times 100$$

where V_{fr} = fibre volumic fraction in %

P = weight

D = density

f = fibre

c = concrete

As mentionned previously, for the first day, fibres were added at the job site and on the second and third day fibres were added on the aggregate conveyor belt at the batch plant. The results are shown in table 13 and graphically on figure 2.

As it can be seen in table 13, when the steel fibres are added at the job site, it becomes very difficult to disperse the fibres homogeneously in the mixer truck. Even when the fibres are added slowly, some balling occurs. As previously explained, the fibres agglomerate at the back of the mixer, and the harshness of the concrete produced prevents the penetration of other fibres.

On the other hand, by spreading the fibres along with the aggregate before mixing the concrete, the resultant mix is very homogeneous and behaves similarly to plain concrete when pouring and finishing.

CONCLUSION

The fibre addition at the jobsite tends to diminish considerably the slump and air content when the concrete is vigorously remixed.

However when fibres are added at the batching plant in an appropriate mix, there is no loss of slump and air content during transportation. There was an average of one hour per load on this project.

A very homogeneous dispersion of fibres is obtained throughout the concrete when fibres are added at the plant, and does not vary during unloading.

7.2 Hardened concrete properties

7.2.1 Drying shrinkage

The drying shrinkage results for the different types of concrete are shown on table 14 and figure 3.

By examining figure 3 we see that:

1) All the concretes swell when they are kept in water.
2) The total shrinkage for steel and polypropylene fibres is aproximately equal to that of the plain concrete.
3) Total shrinkage is not reduced by the presence of fibres, it only tightens the crack pattern.
4) For the 28 days water cured specimens, the drying shrinkage catches up rapidly with the shrinkage for the 7 days water cured specimens.

7.2.2 Modulus of elasticity

The modulus of elasticity measurement was not performed according to ASTM C469-81 specification. ASTM C469-81 states that the specimen must be loaded up to 40% of the ultimate load. In our case, the specimens where loaded only to 20% and the modulus of elasticity was calculated from these results. However all testing was made by using the same method and all the modulus of elasticity were calculated in the same way.

Since the objective of the test was to assess the fibre contribution on modulus of elasticity we feel that the results can be used to make comparative assessment.

In order to assess the contribution of steel and polypropylene fibres on modulus of elasticity, representative specimens of each type of concrete were compared:

i) steel fibre concrete: 5 ACF-2, 5 ACF-4 - 5 ACF - 5

ii) polypropylene fibre concrete: 6PPF-1

iii) plain concrete: 6 OR, 6PP-1

The detailed results are shown on table 15 which is summarized as follows:

Identification	28 days		91 days	
	f'_c MPa mean	E GPa mean	f'_c MPa mean	E GPa mean
Steel fibres / mix #5	38.1	28.7	43.9	33.4
Polypropylene fibers / mix #6	44.9	29.5	50.1	31.6
Plain concrete/ mix #6	38.2	27.5	44.3	34.2

The analysis of the results shows a non-significant contribution to the modulus of elasticity when using steel or polypropylene fibres.

7.2.3 Compressive strength

For each concrete sampled, the compressive strength has been measured on 100 x 200 mm cylinders; results are shown in table 10, 11 and 12.

From table 10, we can evaluate the contribution of steel fibre on compressive strength. The results obtained for 7 and 28 days are as follows:

Age of concrete	f'_c increase with steel fibres in percent.		
	Mix #1	Mix #2	Mix #3
7 d	35 %	24 %	12 %
28 d	24 %	11 %	20 %

The results fluctuate tremendously. These fluctuations can be explained by the lack of homogeneity when concrete was mixed. Furthermore, the compressive strength increase cannot be due totally to the presence of the steel fibres; it should be recalled that the addition of fibres decreased the air content by 2 to 3 %, which certainly helped in increasing the compressive strength.

From these tests, the contribution of the fibres on the compressive strength cannot be assessed with certainty because of the variations of too many parameters.

The compressive strength results of the last five samples with steel fibres shown in tables 11 and 12, are between 36 and 39.1 MPa which is very acceptable. This shows a good reproducibility of the concrete when steel fibres are added at the batch plant.

There was a non-significant increase of the compressive strength when polypropylene fibres were added to the concrete.

7.2.4 Cylinder size influence on f'$_c$ value

The values of f'$_c$ measured on 100 x 200 mm and 150 x 300 mm cylinder are shown on tables 16, 17 and 18. It can be seen that the compressive strength measured on 100 x 200 mm cylinder is in all cases, greater that when it is measured on 150 x 300 mm cylinder. This difference is in the order of 15% for any type of concrete tested.

Therefore it is suggested to use the 150 x 300 mm cylinders to measure the concrete compressive strength when 50 mm steel fibres are used.

7.2.5 Splitting tensile strength

The results of splitting tensile strength at 7 and 28 days for the different types of concrete are shown in table 19. In order to assess the contribution of steel fibre on the splitting tensile strength at 28 days, mix #5 and #6 were compared. The results of the comparison are as follows:

Identification	Tensile strength, 28d MPa
With fibers	5.2-4.6-4.7-4.6-4.7 mean = 4.8 MPa
Without fibers	2.9 - 2.9 - 3.4 mean = 3.1 MPa
With / Without ratio	1.55

The splitting tensile strength for the concrete used on the third day is 55% greater than the specified plain concrete, which is a significant advantage for the design of concrete highways.

We have also computed the 7 to 28 days splitting tensile strength ratio which is indicative of the strength development in time. Thus, for steel fibre concrete (mix #5), 92% of the 28 days is reached at 7 days compared to 83% for the plain concrete (mix #6). The performance at short term is therefore much better.

Not only the splitting tensile strength is increased by 55%, moreover, the steel fibres show a better performance at short term.

For the polypropylene fibres, no significant increase of the splitting tensile strength was noticed when compared to plain concrete.

7.2.6 Flexural strength (controlled deflection)

The mechanical behaviour of a steel fibre reinforced concrete beam can be described as follows:

- before the first crack appears, the concrete and the steel fibre are submitted to an equal elongation. The fibre intervenes very little during elastic deformation.
- after the first crack, there is a sudden drop in the load and sliding of the bridging fibres occurs because $t_i < t_{fa}$ where t_i represents the fibre-matrix interfacial shear strength and t_{fa} is the fibre tensile strength. For the Dramix fibre, t_i has a mean value of 107.6 MPa and t_{fa} is 1276 MPa (ref. 1).

Ref. 1: La Palme Y.R., Hébert L.-P., "Single Fibre Pull-Out Tests on Steel Fibres Embedded in Cement Mortar ". NRCC-IMRI Report #IGM 85-305-219 July 1983.

The flexural strength test was performed on a MTS testing machine with a maximum load capacity of 100 KN. The load was applied at third-point and defection was set at a constant rate of 0,5 mm/min. An X-Y plotter recorded continuously the load-deflection curve. The load at proportional limit is calculated were the curve deviates from linearity. This is the elastic limit of the composite material. The flexural modulus of rupture is calculated from the maximum load the prism can sustain.

The flexural strength for 7, 28 and 91 days are shown in table 20. The steel fibre reinforced concrete, the curves show a ductile behaviour of the material and a great capacity to absorb energy during deflection. The work required to pull-out the steel fibres from the concrete matrix increases dramatically and transforms the concrete, a brittle material into a quasi-ductile material. It is in the plastic deformation that the concrete mechanical properties are best improved. The work of rupture improvement can be quantified by measuring the area under the load-deflection and comparing to the work up to the proportional limit. Unfortunately, it has been impossible to quantify the exact work ratio, since no provisions were made to account for the testing machine deformation.

However, it was noticed that the work of rupture is much greater for steel fibre concrete than for polypropylene fibre concrete.

Table 21 shows percentage increase of fibre concrete for proportional limit and for modulus of rupture at different ages.

For steel fibre concrete, the increase in strength as a function of the age of the concrete can be explained by a densification of hydration products around the fibres, thus increasing the fibre-concrete interfacial strength. Even more, as the concrete ages, the hooks at each fibre end makes the fibre more and more difficult to slip.

For polypropylene fibres, very little slip occurs mainly due to the relative fibre roughness. The fibres tend to elongate up to rupture. Even though polypropylene fibres have a tensile strength of 400 to 700 MPa, their modulus of elasticity is lower than that of the concrete and therefore contributes very little to the flexural strength.

7.2.7 Fatigue resistance

Fatigue resistance measurement was not originally planned, but since this property is of very great importance, it was decided to run a few tests at 28 days.

A total of 7 prisms of 100 x 100 x 400 mm were tested for fatigue resistance with third-point loading arrangement. The cyclic loading with a constant amplitude ranging from 10 to 60 % of the modulus of rupture was applied to six samples. Only one steel fibre concrete was loaded up to 90% of the modulus of rupture. The failure is defined as the inability to sustain load.

The fatigue testing was performed on a closed loop servo-controlled hydraulic ram system able to apply a fixed range of loading. The range of loading was controlled electronically so that complete cyclic loading was possible.

The cyclic rate of loading was 20 Hz for all tests.

The results are shown on table 22.

The fatigue failure mechanism is developped in three stages.

1) crack initiation
2) slow crack propagation
3) finally, rapid crack propagation up to failure.

Each of these stages would be distinct in a large concrete specimen. However, for small prisms (100 x 100 x 400mm) of plain concrete, these stages follow very rapidly.

During the crack propagation in a polypropylene fibre reinforced concrete, there is a stress redistribution along the fibre up to each fibre's tips and a new crack starts until it reaches another fibre, and so on. The propagation is therefore slowed down, but because of the few low modulus fibres bridging the crack, the latter cannot sustain the stress alone.

For steel fibre reinforced concrete, the same stress distribution phenomenon occurs. However, the fibre's stiffness and high tensile strength allows a stress distribution in a much larger matrix volume. The fibres do not break, instead they deform elastically.

Two 5ACF prisms were submitted to two million and ten million cycles. A very fine crack appeared between 1.5 to 1.6 million cycles on both prisms. This crack had propagated very slowly over ¼ the height and was barely visible to the naked eye.

After fatigue testing, the prism marked 5 ACF (1) was tested in flexure. The result is shown in table 20. The load and deflection at proportional limit has hardly changed. However, the work of failure has increased by 54%.

For the prism marked 5 ACF (2), it was set into the salt fog cabinet, after the fatigue test, for 1100 hours and then was tested in flexure at 91 days. The result, in table 20, shows that the modulus of rupture and the work of failure had increased by 12 and 37% respectively.

Batson (ref. 2) reports an explanation based on the shrinkage of the concrete during curing and relaxing of residual tension stress due to shrinkage by the action of the cyclic loading.

7.2.8 Impact resistance

The assessment of fibre concrete impact resistance has been characterized, although the quantitative measurement of impact on composite materials are very difficult. A full description of the method used, appears in reference 3, and can be summarized as follows:

- A standard, manually operated, 10 pounds (4.54 kg) compaction hammer falls with an 18-inch drop (460 mm) (ASTM-D-1557) on a 2½ inches (63,5 mm) hardened steel ball resting on the 6 inches (152.4 mm) diameter by 2½ inches (63.5 mm) thick concrete specimen. The specimen is centered on a steel plate where 4 lugs are welded on a 6 3/8 inches (162 mm) diameter. The number

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Ref. 2 - Batson G., BallC., Bailey L., Landers E., Hooks J. - "Flexural Fatigue Strength of Steel Fibres Reinforced Concrete Beams". J.ACI, Vol. 69, N° 11, 1972, pp. 673-677.

Ref. 3 - Schrader E.K., "Impact Resistance and Test Procedures for Concrete", J. ACI, Vol. 78, N° 2, 1981, pp. 141-146.

of blows required to cause first crack and ultimate failure are recorded. First crack is defined as being the first visible crack on the top and ultimate failure is defined as the number of blows required to open the crack in the specimen sufficiently so that the pieces of concrete touches three of the four lugs.

After 28 days of moist curing, only 2 specimens of each type of concrete were tested. The results are shown in table 23. At 91 days, 8 specimens were tested. The high and low values were discarded. For each type or concrete the remaining mean value and standard deviation are shown in table 23.

The great scatter in the results is likely due to the non-uniform fibre distribution, from one test to the other, at the point of impact.

The number of blows required from the first crack up to the ultimate failure is only 3 for the plain concrete, 6 for the polypropylene fibre concrete, and 75 for steel fibre reinforced concrete. It is obvious that generally fibre increases significantly the impact resistance of plain concrete.

7.2.9 Abrasion resistance

Figures 4, 5 and 6 show the abrasion resistance of different types of concrete.

1) Figure 4

The abrasion resistance is very similar even though the coarse aggregate volume is lesser in mix #5 compared to mix #6. Actually, there is very little abrasion resistance difference among plain, polypropylene or steel fibre concretes.

2) Figure 5

The abrasion resistance of steel fibre reinforced concrete made from different mixes are shown on this figure. The coarse aggregate volume fraction does not seem to have a significant influence on the abrasion resistance.

3) Figure 6

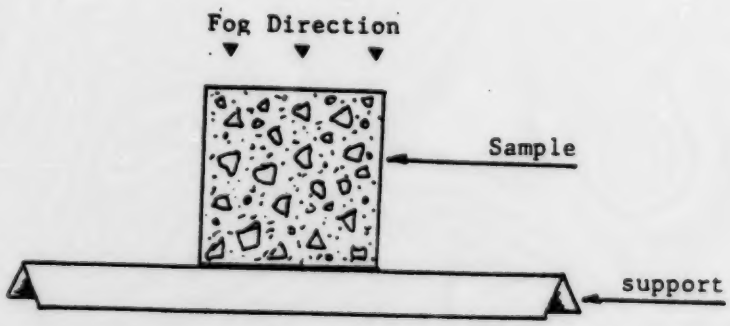
As in the case of the laboratory specimens, the cores taken from experimental slabs containing steel fibres (mix #5), withstand abrasion just as well as the plain and polypropylene fibre concrete with a higher coarse aggregate content (mix #6).

7.2.10 Corrosion of steel fibres in concrete

The practice shows that wherever de-icing salts are used, steel rebars are rapidly corroded by the chloride corrosive action and blows up the concrete under steel expansion. Hence, the importance to evaluate the behaviour of steel fibres exposed to an aggressive environment.

This aggressive environment was re-created and it's severity to chloride exposure was increased by using a salt fog cabinet in accordance to ASTM-B-117 standard.

The salt solution is made up of 5 p/p calcium chloride (supplied by the Québec Ministry of Transport) diluted in 95 p/p of de-ionized water. The fog is produced inside the cabinet by automatically atomizing the solution with an air pressure between 76 to 79 kPa, under a constant ambiant temperature of 35°C. The samples are set on supports continuously through the test period as shown on the following figure:



The samples are 76 mm cubes cut from longer prisms. All specimens had 2 vertical faces sawed and 2 mould finished. The bottom face was also mould-finished and the top surface was trowel finished. The samples were set in the fog cabinet after a 28 days initial water curing.

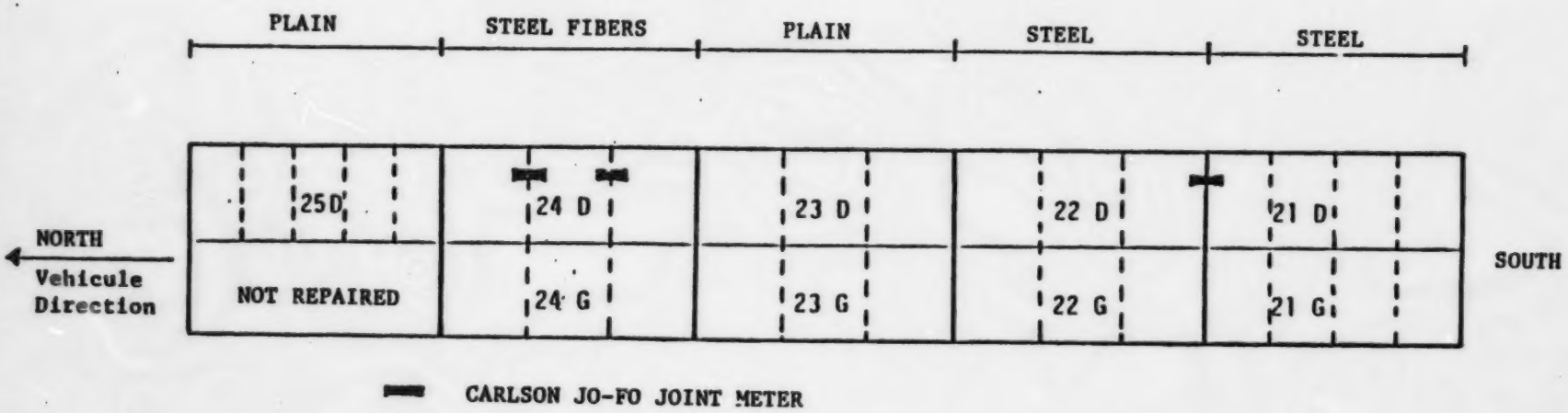
To measure the quality and the quantity of fog, beakers are placed near the samples. Results are as follows:

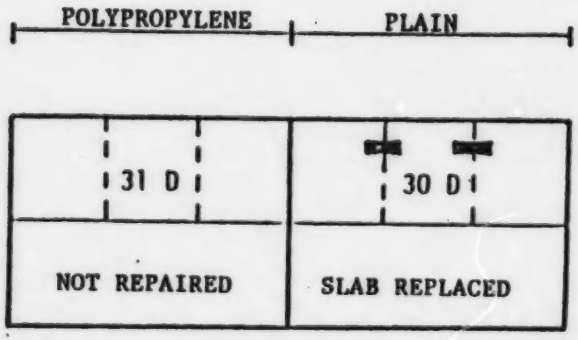
	Measured	ASTM B-117
Temperature	35 ± 0°C	35 ± 1.7°C
Quantity of solution (ml/hour)	1.06 to 1.31	1 to 1
pH	6.6 to 7.0	6.5 to 7.2
Salt fraction %	4.7 to 5.8	5 ± 1
Pressure k Pa	76 to 79	69 to 172

Three samples of each type of concrete were exposed continuously for 1600 hours. After the exposure period, the samples were withdrawn and visually examined. The calcium chloride did not affect neither the plain nor the polypropylene fibre concrete. For the steel fibre reinforced concrete, only the tips of the exposed fibres visible on the sawed surfaces had severely corroded.

The microscope examination of a cut perpendicular to the exposed surface shows that the majority of the fibres covered by the cement paste, have not corroded.

Only a low number of these fibres have corroded up to a maximum depth of 3.2 mm. (fig. 7).





SLAB	CONCRETE MIX
21 D	# 1 et # 2
21 G	# 5
22 D	# 2 et # 3
22 G	# 5
23 D	# 3
23 G	# 6
24 D	# 4 et # 5
24 G	# 5
25 D	# 6
30 D	# 6
31 D	# 6

Figure 1 - TYPE OF CONCRETE USED AND IDENTIFICATION OF EXPERIMENTAL CONCRETE SLABS.

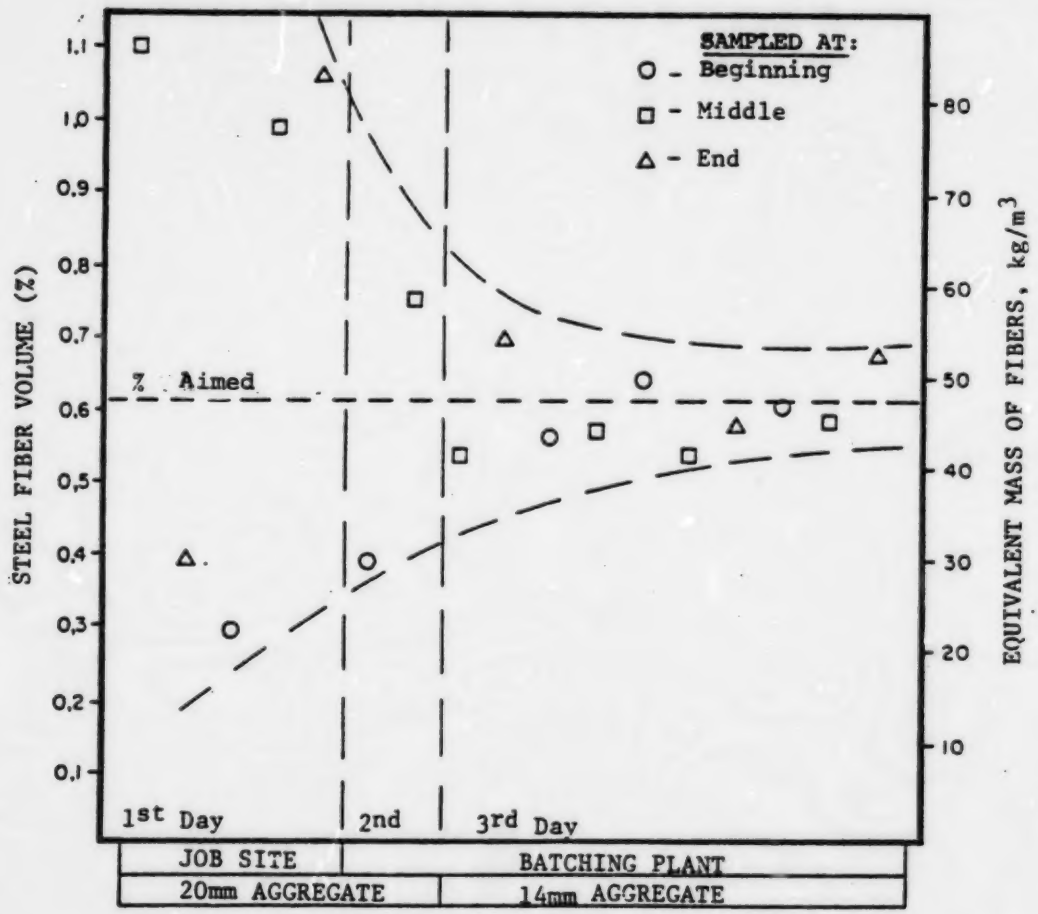


Figure 2- FIBER CONTENT IN CONCRETE WHEN ADDED AT JOB SITE OR AT BATCHING PLANT.

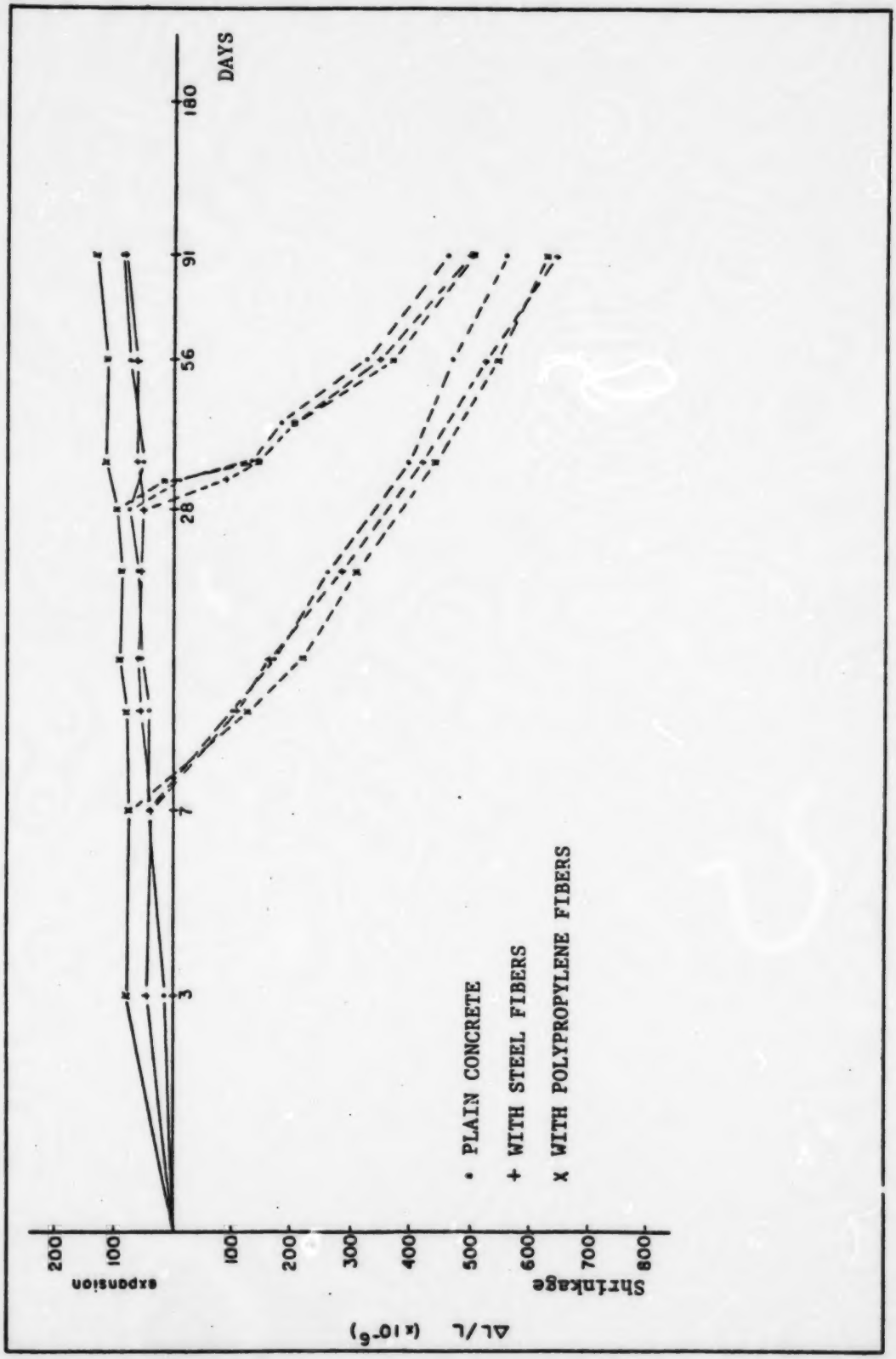


Figure 3- DRYING SHRINKAGE OF THE DIFFERENT TYPES OF CONCRETE KEPT IN WATER FOR 7 AND 28 DAYS.

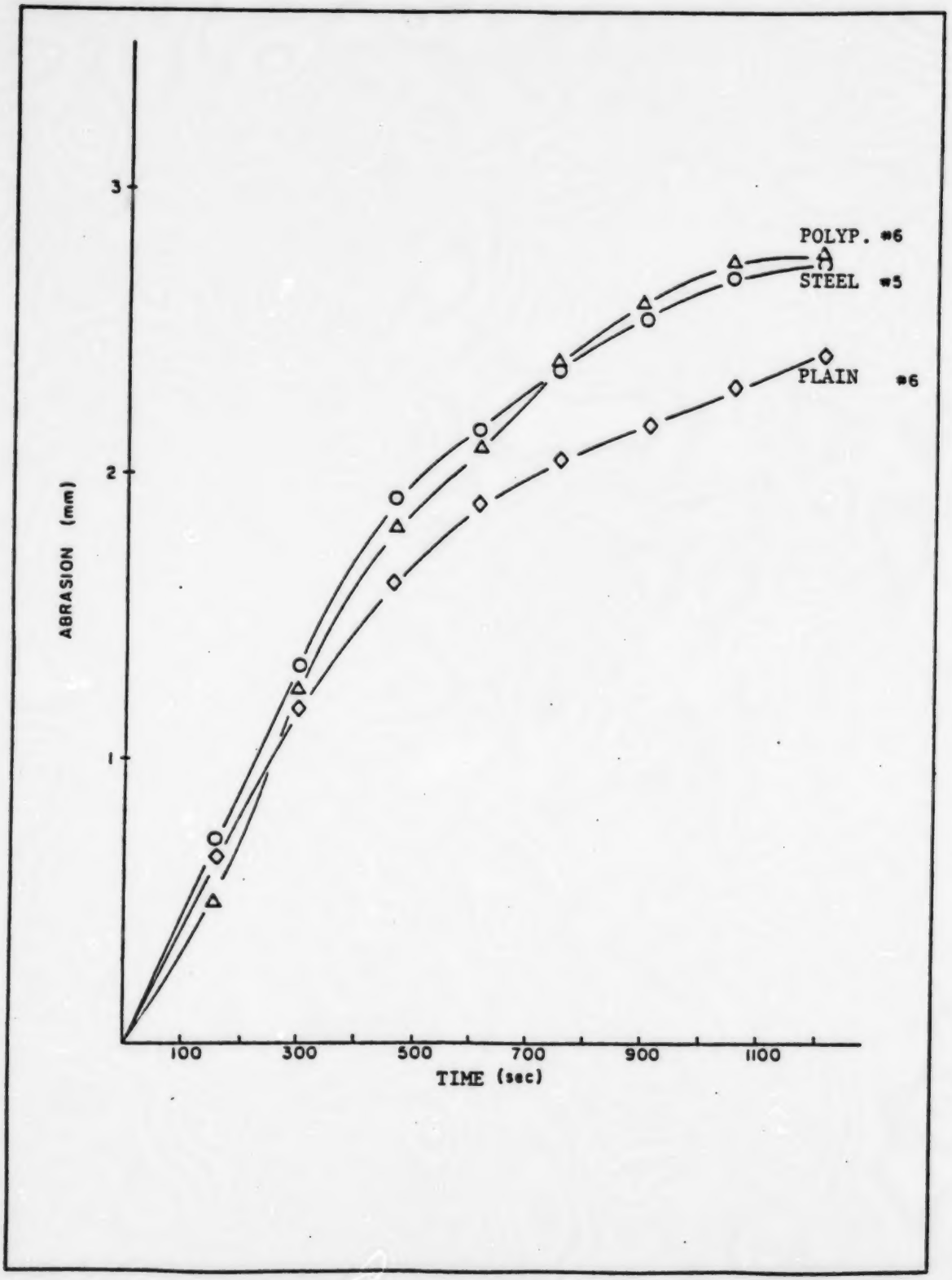


Figure 4- ABRASION RESISTANCE AT 48 DAYS

Steel	Polypropylene	Plain
5 ACF-2	6 PPF-1	6 OR
5 ACF-4		6 PP-1

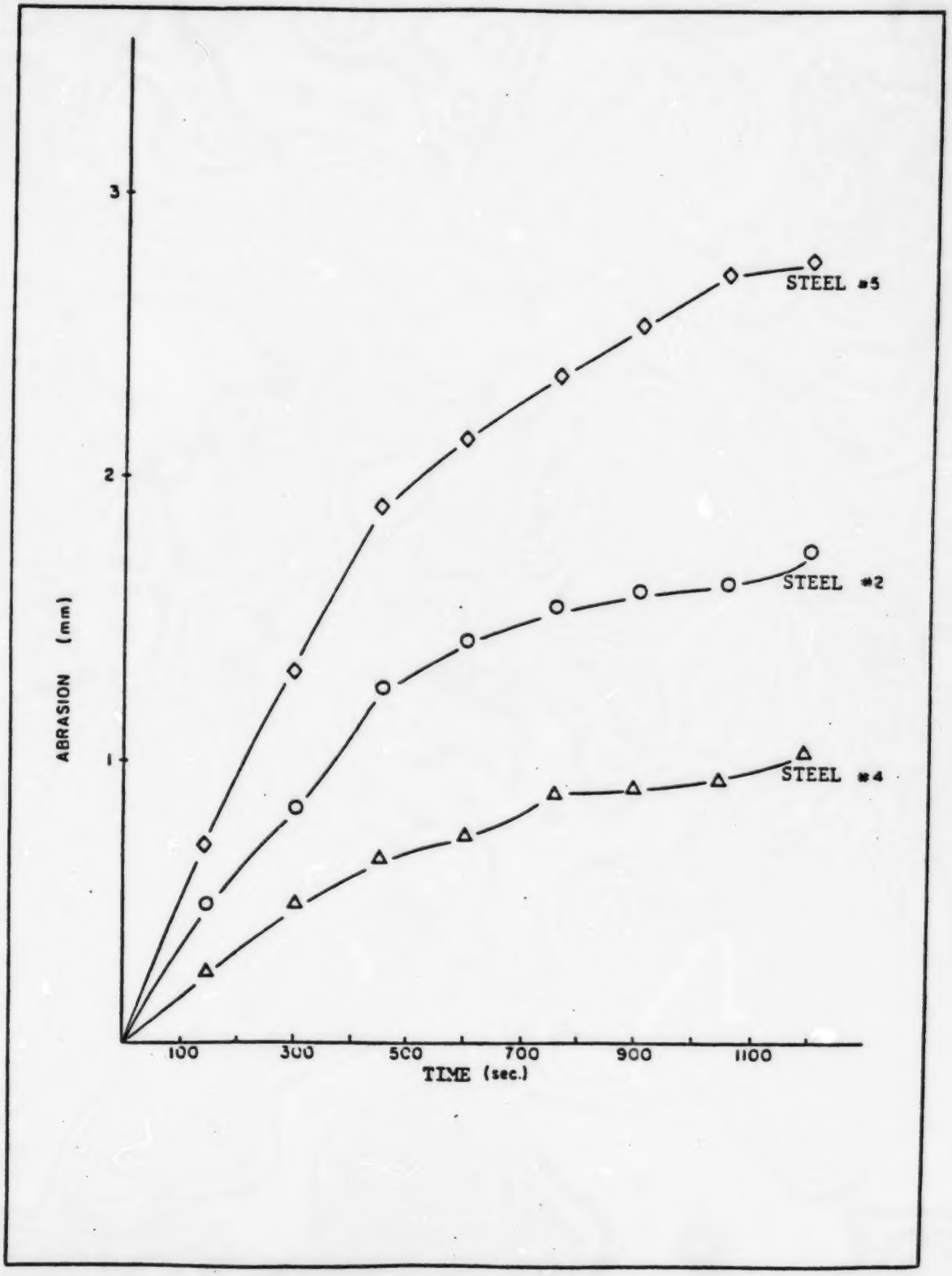


Figure 5- ABRASION RESISTANCE AT 48 DAYS FOR DIFFERENT STEEL FIBERS REINFORCED CONCRETE MIX DESIGN.

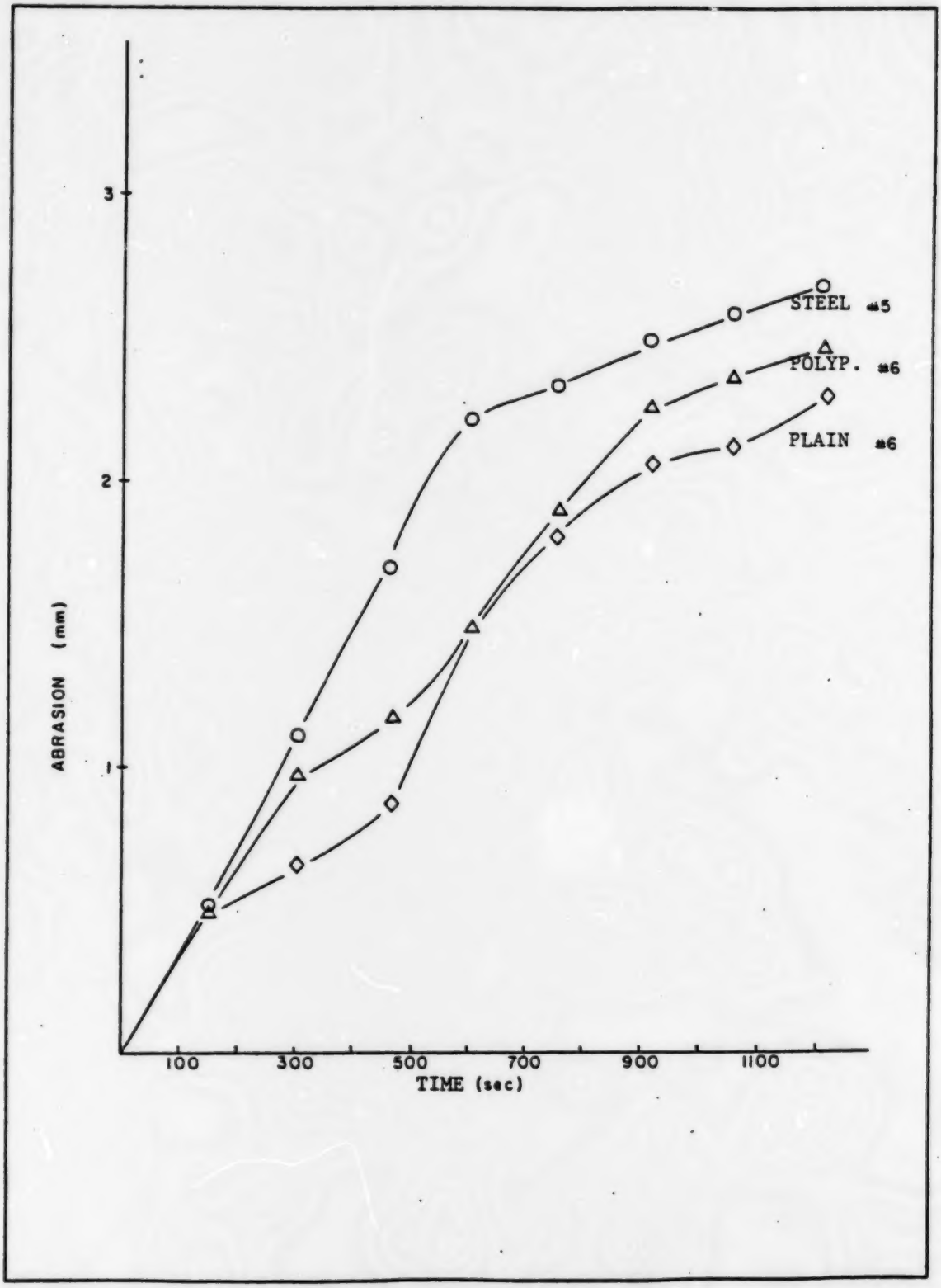
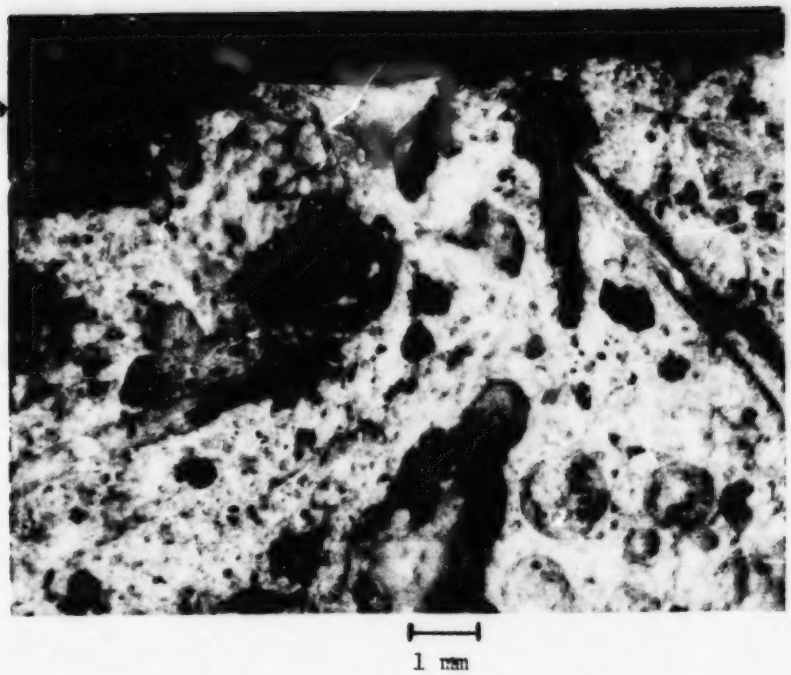


Figure 6- ABRASION RESISTANCE AT 48 DAYS MESURED ON CORES TAKEN FROM EACH TYPE OF CONCRETE.
MIX 5ACF-2, 6 PPF-1, 6 OR.



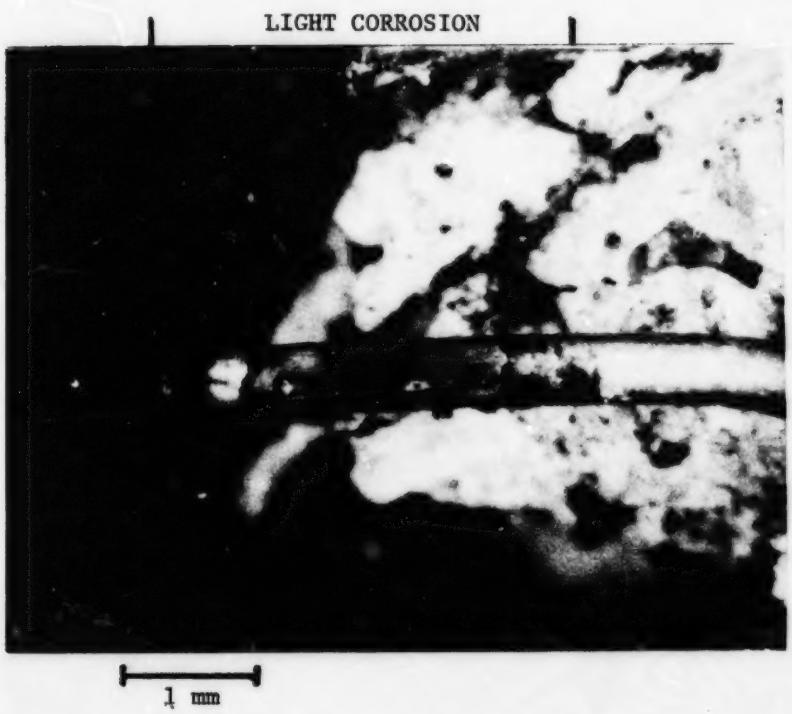


Figure 7- STEEL FIBER CORROSION EXPOSED TO SALT FOG.

SLAB IDENTIFICATION	TYPE OF CONCRETE	SLAB THICKNESS (mm)			JOINT SPACING (m)	JOINT DEPTH (mm)	DOWELS
		THEORITICAL	MEASURED				
			VARIAT.	AVER.			
21 D	STEEL FIBERS	125	-	-	4.57	1) 36 2) 46 3) 47	NO
21 G	STEEL FIBERS	125	120-142	133	4.57	1) 44 2) 44 3) 45	NO
22 D	STEEL FIBERS	150	148-168	160	6.1	1) 58 2) 55	NO
22 G	STEEL FIBERS	150	145-169	155	6.1	1) 38 2) 58	NO
23 D	PLAIN	175	171-193	182	6.1	1) 34 2) 45	YES
23 G	PLAIN	175	172-198	186	6.1	1) 37 2) 39	YES
24 D	STEEL FIBERS	175	-	-	6.1	1) 50 2) 61	NO
24 G	STEEL FIBERS	175	153-185	168	6.1	1) 53 2) 57	NO
25 D	PLAIN	200	-	-	3.64	1) 43 2) 49 3) 40 4) 55	YES
30 D	PLAIN	225	209-229	218	6.1	1) 51 2) 51	YES
31 D	POLYPROPYLENE	225	182-209	194	6.1	1) 52 2) 52	NO

TABLE I - PHYSICAL CHARACTERISTICS OF EXPERIMENTAL SLABS.

NATURE OF MATERIAL	PHYSICAL CHARACTERISTICS
COARSE AGGREGATE 10 + 20 mm (Varennes) 14 mm (Laval)	ABSORPTION: Varennes 0.6 Laval 0.8 d_{ssd} : 2.55 2.70
NATURAL SAND (St-Félix)	ABSORPTION: 0.5 d_{ssd} 2.65 F.M. 2.65
TYPE 10 CEMENT Independant	d : 3.14
STEEL FIBERS Dramix TM ZP 50/0,50 (Bekaert)	LENGTH : 50 mm DIAMETER : 0.50 mm DENSITY : 7.85 ASPECT RATIO: 100
POLYPROPYLENE FIBERS Fibermesh TM	LENGTH : 52 mm DENSITY : 0.9
SUPERPLASTICIZER Mighty 150	DENSITY : 1.20 SOLIDS : 42%

TABLE 2 - MATERIAL PHYSICAL CHARACTERISTICS.

SIEVE		PASSING CUMULATIVE (%)			
		NATURAL SAND	STONE 10 mm	STONE 14 mm	STONE 20 mm
mm	28				100
	20			100	90
	14		100	79	8
	10	100	98	28	2
	5	95	19	2	
	2.5	89	4		
	1.25	75	2		
µm	630	43			
	315	18			
	160	6			
	80	2			

IDENTIFICATION	COARSE AGGREGATE PROPORTIONS		
	10 mm	14 mm	20 mm
Mix # 1	15%	38%	47%
Mix # 2	16%	39%	45%
Mix # 3	16%	40%	44%
Mix # 4	20%	41%	39%
Mix # 5	59%	41%	0%
Mix # 6	15%	37%	48%

TABLE 3 - FINE AND COARSE SIEVE ANALYSIS AND PROPORTIONS OF COARSE AGGREGATE FOR THE DIFFERENT MIXES.

FRESH CONCRETE	SLUMP	1 per load								
	AIR CONTENT	1 per load								
	UNIT WEIGHT	1 per load								
	HOMOGENEITY	3 per load								
	TEST DESCRIPTION	AGE OF CONCRETE					NUMBER OF SAMPLES			
		7d	28d	91d	1 an	2 ans	100 x 200	150 x 300	100 x 100 x 400	75 x 75 x 300
HARDENED CONCRETE	Compression 100 x 200	3	3	3	3	3	15			
	Compression 150 x 300	3	3	3	3			12		
	Controlled Deflection	3	3	3	3				12	
	Shrinkage	2+2	2						6	
	Elastic Modulus		2	2	2			6		
	Splitting Tensile	3	3		3			9		
	Abrasion Impact		2	2	2			6		
	Fatigue		2						2	
	Porosity			1			1			
	Corrosion		1							1
COMPLETE SAMPLING TOTAL							16	33	20	1
First day	3 complete sampling						48	99	60	3
Second day	4 complete sampling						64	132	80	4
Third day	2 complete sampling						32	66	40	2

TABLE 4 - COMPLETE SAMPLING PROGRAM.

SLUMP	1 per load			
AIR CONTENT	1 per load			
UNIT WEIGHT	1 per load			
TEST DESCRIPTION	AGE OF CONCRETE		NUMBER OF SAMPLES	
	7d	28d	100 x 200	150 x 300
COMPRESSION	3	3	6	-
SPLITTING TENSILE	-	3	-	3
Total	-	-	6	3

TABLE 5 - CONTROL SAMPLING PROGRAM.

TEST DESCRIPTION	AGE OF CONCRETE						NUMBER OF SAMPLES	
	28d	48d		180d	1 an	2ans	100 x 200	150 x 300
COMPRESSION	3	-	-	3	3	3	12	-
ABRASION	-	1	-	1	1	1	-	4
AIR SPACING	-	-	2	2	2	2	-	8
IMPACT	-	1	-	1	1	1	-	4
TOTAL	-	-	-	-	-	-	12	16

TABLE 6 - HARDENED CONCRETE CORING PROGRAM.

		1st DAY SAMPLING	2nd DAY SAMPLING	3rd DAY SAMPLING
DATE		84/10/18	84/10/23	84/10/25
CONCRETE MIX SAMPLED		#1, #2, #3	#4, #5, #6	#5
NUMBER OF SAMPLING	Complete	4	5	4
	Control	3	4	2
SAMPLED CONCRETE	Complete	1 ACF, 2 AC, 3 AC, 3 ACF	P4ACF, P5ACF-1, 5ACF-1 6PP-6PPF	P5ACF-2, 5ACF-3 P5ACF-4, 5ACF-5
	Control	1 AC, 2 ACF, 3 OR	4 ACF, 6 OR, 5PP-1, 6PPF-1	5 ACF-2, 5 ACF-4

TABLE 7 - SAMPLED CONCRETE IDENTIFICATION FOR EACH SAMPLING PROGRAM.

		STEEL FIBER CONCRETE		POLYPROPYLENE FIBER CONCRETE		PLAIN CONCRETE
ADDITION OF FIBERS		PLANT	JOB SITE	PLANT	JOB SITE	NO FIBERS
CONCRETE MIX	# 1		YES			
	# 2		YES			
	# 3		YES			YES
	# 4	YES				
	# 5	YES				
	# 6				YES	YES

TABLE 8 - MIX USED FOR EACH TYPE OF CONCRETE.

			MIX DESIGN USED					
			#1	#2	#3	#4	#5	#6
COMPOSITION kg/m³	CEMENT		370	370	370	370	390	360
	WATER		170	170	170	174	179	160
	SAND (SSD)		770	800	830	860	940	760
	STONE (SSD)	10 mm	150	150	150	165	440	150
		14 mm	370	370	370	350	310	380
		20 mm	465	435	405	330	-	490
		Total	985	955	925	845	750	1020
ADMIXTURES ml/100kg cement	WATER REDUCING (TCDA XA)		250	250	250	250	250	250
	AIR ENTRAIMENT (AIREX L)		30	30	30	30	30	30
	SUPERPLASTICIZER (MULCOPLAST)		-	-	-	-	-	600

TABLE 9 - CONCRETE MIX DESIGN USED FOR THE EXPERIMENTAL SLABS.

		1st LOAD		2nd LOAD		3rd LOAD		4th LOAD
TYPE OF CONCRETE		STEEL FIBERS		STEEL FIBERS		STEEL FIBERS		PLAIN CONCRETE
MIX + QUANTITY		# 1 , 8 m^3		#2 , 7,5 m^3		#3 , 8 m^3		#3
SLAB No.		21 D		21-22 D		22 D		23 D
DELIVERY TIME		102 min		82 min		104 min		55 min
MIXING TIME WITH FIBERS		11 min		10 min		5 min		-
CONCRETE		Before Fibers	With Fibers	Before Fibers	With Fibers	Before Fibers	With Fibers	NO FIBERS
SAMPLING		Complete 1 AC	Control 1 ACF	Control 2 AC	Complete 2 ACF	Control 3 AC	Control 3 ACF	Complete 3 OR
WATER ADDED (L)		15	15	15	10	15	-	-
SUPERPLASTICIZER (L)		2.3	4.7	3.7	2.6	9.8	-	-
SLUMP (mm)		100	120	125	70	180	40	85
AIR (%)		6.2	4.5	6.5	3.2	5.4	3.3	7.7
UNIT WEIGHT (kg/m^3)		2290	2320	2270	2360	2270	2380	2260
COMPRESSION MPa (100 X 200)	7 d	29.6	40.2	29.7	36.8	30.1	33.8	31.4
	28 d	34.9	43.4	36.7	40.9	36.0	43.2	36.2
	91 d	41.2	-	-	48.6	-	-	41.0
	1 year							
	2 years							
TENSILE MPa	7 d	2.4	-	-	4.5	-	-	2.5
	28 d	2.8	4.2	2.5	5.3	2.6	5.6	2.9
	1 year		-	-		-	-	
FLEXURAL MPa	7 d	4.7	-	-	5.5	-	-	4.9
	28 d	5.0	-	-	6.0	-	-	5.3
	91 d	5.2	-	-	6.3	-	-	5.4
	1 year		-	-		-	-	

TABLE 10 - RESULTS OF THE FIRST DAY SAMPLING.

		1st LOAD		2nd LOAD		3rd LOAD	4th LOAD		5th LOAD	
TYPE OF CONCRETE		STEEL FIBERS		STEEL FIBERS		PLAIN CONCRETE	POLYPROPYLENE FIBERS		POLYPROPYLENE FIBERS	
MIX + QUANTITY		# 4 6.5 m^3		# 5 6.5 m^3		#6. 9m^3	# 6 7.5 m^3		# 6 7.5 m^3	
SALB No.		24 D		24 D		25 D	31 D		31 D	
DELIVERY TIME		77 min		52 min		54 min	71 min		66 min	
MIXING TIME WITH FIBERS		-		-		-	5 min		5 min	
CONCRETE		PLANT	JOB SITE	PLANT	JOB SITE	JOB SITE	BEFORE FIBERS	WITH FIBERS	BEFORE FIBERS	WITH FIBERS
SAMPLING		CONTROL P4ACF	COMPLETE 4 ACF	CONTROL P5ACF-1	CONTROL 5 ACF-1	COMPLETE 6 OR	COMPLETE 6 PP-1	COMPLETE 6 PPF-1	CONTROL 6 PP-2	CONTROL 6 PPF-2
WATER ADDED (L)		-	-	-	-	-	15	5	15	-
SUPERPLASTICIZER (L)		-	-	-	-	-	3	3	5	-
SLUMP (mm)		75	50	90	110	90	90	75	135	70
AIR (%)		6.5	3.2	7.0	6.5	6.2	6.0	5.1	5.4	4.4
UNIT WEIGHT (kg/m^3)		-	2340	-	2250	2270	2280	2310	2320	2360
COMPRESSION MPa (100 X 200)	7 d	31.5	36.0	33.5 *	32.8	33.0	34.0	40.5	39.8	41.4
	28 d	37.4	43.1	40.8	37.7	34.9** 37.6	38.8	40.4** 44.6	44.3	46.2
	91 d	-	47.6	-	-	45.6	43.0	50.1	-	-
	1 year									
	2 years									
TENSILE MPa	7 d	-	4.2	-	-	2.4	2.4	3.0	-	-
	28 d	3.8	4.9	4.2	5.2	2.9	2.9	3.1	3.4	2.9
	1 year	-		-	-				-	-
FLEXURAL MPa	7 d	-	4.7	-	-	4.7	4.8	5.0	-	-
	28 d	-	5.0	-	-	-	4.8	5.4	-	-
	91 d	-	5.5	-	-	4.9	5.3	5.5	-	-
	1 year	-		-	-				-	-

TABLE 11 - RESULTS OF THE SECOND DAY SAMPLING.

* TESTED AT 8 DAYS

** TEST ON CORES.

		1st LOAD		2nd LOAD		3rd LOAD		4th LOAD	
TYPE OF CONCRETE		STEEL FIBERS		STEEL FIBERS		STEEL FIBERS		STEEL FIBERS	
MIX + QUANTITY		# 5 , 9 m^3		# 5 , 8 m^3		# 5 , 8 m^3		# 5 , 8 m^3	
SLAB No.		21 G		21-22 G		22-24 G		24 G	
DELIVERY TIME		80 min		84 min		82 min		126 min	
MIXING TIME WITH FIBERS		-		-		-			
CONCRETE		PLANT	JOB SITE	PLANT	JOB SITE	PLANT	JOB SITE	PLANT	JOB SITE
SAMPLING		CONTROL P5ACF-2	COMPLETE 5 ACF-2	-	CONTROL 5ACF-3	CONTROL P5ACF-4	COMPLETE 5 ACF-4	-	CONTROL 5 ACF-5
WATER ADDED (L)		-	15	-	16	-	15	-	8
SUPERPLASTICIZER (L)		-	5	-	6	-	4	-	5
SLUMP (mm)		115	110	-	100	110	95		100
AIR (%)		8.2	6.5	-	7.2	7.6	8.0		6.5
UNIT WEIGHT (kg/m^3)		-	2280		2270	-	2230		2270
COMPRESSION MPa (100 X 200)	7 d	38.4	32.9		32.3	31.8	32.8		34.0
	28 d	44.7	37.4** 39.1		38.3	38.6	36.0		39.1
	91 d	-	44.5	-		-	42.6		44.6
	1 yr.			-					
	2 yrs			-					
TENSILE MPa	7 d	-	4.2	-	-	-	4.2	-	-
	28 d	4.9	4.6	-	4.7	3.9	4.6	-	4.7
	1 yr.	-		-	-	-		-	-
FLEXURAL MPa	7 d	-	5.8	-	-	-	5.6	-	-
	28 d	-	6.2	-	-	-	5.9	-	-
	91 d	-	6.4	-	-	-	5.6	-	-
	1 yr.	-		-	-	-		-	-

TABLE 12 - RESULTS OF THE THIRD DAY OF SAMPLING.

** TEST ON CORES.

	DAY	MAXIMUM SIZE AGG.	LOAD	SAMPLE TAKEN	V_{fr} %	MEAN	STANDARD DEVIATION
FIBERS ADDED AT JOB SITE	1st	20 mm	1	M	1.096	0.77	0.39
		20 mm	1	E	0.387		
		20 mm	2	B	0.296		
		20 mm	2	M	0.990		
		20 mm	3	E	1.058		
FIBERS ADDED AT BATCHING PLANT	2nd	20 mm	4	B	0.390	0.59	0.09
		20 mm	4	M	0.753		
	3rd	14 mm	5-1	M	0.535		
		14 mm	5-1	E	0.665		
		14 mm	5-2	B	0.564		
		14 mm	5-2	M	0.569		
		14 mm	5-3	B	0.637		
		14 mm	5-3	M	0.536		
		14 mm	5-3	E	0.573		
		14 mm	5-4	B	0.600		
		14 mm	5-4	M	0.579		
		14 mm	5-4	E	0.667		

TABLE 13 - STEEL FIBERS VOLUMETRIC FRACTION FOUND IN THE MIXED CONCRETE:

B = BEGINNING OF LOAD

M = MIDDLE

E = END.

TYPE OF CONCRETE	PLAIN			STEEL FIBERS			POLYPROPYLENE FIBERS		
NUMBER OF SAMPLES	3			4			1		
TYPE OF CURING	WATER	WATER (7d)	WATER (28d)	WATER	WATER (7d)	WATER (28d)	WATER	WATER (7d)	WATER (28d)
1 d									
3 d	+13			+50			+81		
7 d	+48	+48		+45	+ 45		+78	+ 78	
11 d	+42	-102		+55	-105		+81	-125	
14 d	+54	-171		+59	-164		+92	-221	
21 d	+60	-261		+55	-290		+88	-309	
28 d	+78		+78	+55		+55	+97		+97
32 d			- 7			-89			+18
35 d	+50	-397	-136	+60	-424	-141	+110	-441	-143
42 d			-186			-202			
56 d	+70	-470	-326	+73	-529	-343	+110	-552	-368
91 d	+85	-562	-460	+86	-641	-498	+132	-632	-500
180 d									

TABLE 14 - DRYING SHRINKAGE OF CONCRETE CURED FOR 7 DAYS AND 28 DAYS IN WATER (SHRINKAGE X 10^{-6}).

Identification	28 DAYS		91 DAYS		1 YEAR	
	f'_c (MPa)	E (GPa)	f'_c (MPa)	E (GPa)	f'_c (MPa)	E (GPa)
1 AC	34.9	30.9	41.1	36.2		
2 ACF	40.9	34.2	48.6	35.6		
3 OR	36.2	29.2	41.0	30.3		
4 ACF	43.1	29.8	47.6	31.4		
5 ACF-2	39.1	28.8	44.5	33.7		
5 ACF-4	36.0	29.8	42.6	30.9		
5 ACF-5	39.1	27.6	44.6	35.6		
6 OR	37.6	28.2	45.6	31.7		
6 PP-1	38.8	26.7	42.9	36.7		
6 PPF-1	44.9	29.5	50.1	31.6		

TABLE 15 - COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY OF DIFFERENT TYPES OF CONCRETE.

	FIRST DAY					
	1st LOAD		2nd LOAD		4th LOAD	
TYPE OF CONCRETE	STEEL FIBERS		STEEL FIBERS		PLAIN CONCRETE	
MIX	# 1		# 2		# 3	
SAMPLING	COMPLETE 1 AC		COMPLETE 2 ACF		COMPLETE 3 OR	
CONCRETE	BEFORE FIBERS		WITH FIBERS		NO FIBERS	
CYLINDER SIZE	100x200	150x300	100x200	150x300	100x200	150x300
7 days	29.6	27.4	36.8	32.5	31.4	26.6
28 days	34.9	33.2	40.9	39.3	36.2	32.0
91 days	41.2	35.7	48.6	44.3	41.0	35.1
1 year						
2 years						

TABLE 16 - INFLUENCE OF CYLINDER SIZE ON COMPRESSIVE STRENGTH OF CONCRETE FOR THE FIRST DAY.

	SECOND DAY							
	1st LOAD		3rd LOAD		4th LOAD		4th LOAD	
TYPE OF CONCRETE	STEEL FIBERS		PLAIN CONCRETE		POLYPROPYLENE FIBERS		POLYPROPYLENE FIBERS	
MIX	# 4		# 6		# 6		# 6	
SAMPLING	COMPLETE 4 ACF		COMPLETE 6 OR		COMPLETE 6 PP-1		COMPLETE 6 PPF-1	
CONCRETE	WITH FIBERS		NO FIBERS		BEFORE FIBERS		WITH FIBERS	
CYLINDER SIZE	100x200 mm	150x300 mm	100x200 mm	150x300 mm	100x200 mm	150x300 mm	100x200 mm	150x300 mm
7 days	36.0	30.5	33.0	27.7	34.0	28.3	40.5	29.7
28 days	43.1	38.0	37.6	33.4	38.8	33.6	44.6	37.0
91 days	47.6	41.5	45.6	38.3	43.0	37.4	50.1	40.7
1 year								
2 years								

TABLE 17 - INFLUENCE OF CYLINDER SIZE ON COMPRESSIVE STRENGTH OF CONCRETE FOR THE SECOND DAY.

	THIRD DAY			
	1st LOAD		3rd LOAD	
TYPE OF CONCRETE	STEEL FIBERS		STEEL FIBERS	
MIX	# 5		# 5	
SAMPLING	COMPLETE 5 ACF-2		COMPLETE 5 ACF-4	
CONCRETE	WITH FIBERS		WITH FIBERS	
CYLINDER SIZE	100x200 mm	150x300 mm	100x200 mm	150x300 mm
7 days	32.9	29.3	32.8	27.5
28 days	39.1	34.9	36.0	32.9
91 days	44.5	39.0	42.6	35.8
1 year				
2 years				

TABLE 18 - INFLUENCE OF CYLINDER SIZE ON COMPRESSIVE STRENGTH OF CONCRETE FOR THE 3rd DAY.

Identification	SPLITTING TENSILE STRENGTH MPa			
	7 days	28 days	1 year	$\frac{7}{28}$ d. RATIO %
1 AC	2.4	2.8	-	87
1 ACF	-	4.2	-	-
2 AC	-	2.5	-	-
2 ACF	4.5	5.3		85
3 AC	-	2.6	-	-
3 ACF	-	5.6	-	-
3 OR	2.5	2.9		85
P 4ACF	-	3.8	-	-
4 ACF	4.2	4.9		87
P 5ACF-1	-	4.2	-	-
5 ACF-1	-	5.2	-	-
P 5ACF-2	-	4.9	-	-
5 ACF-2	4.2	4.6		91
5 ACF-3	-	4.7	-	-
P 5 ACF-4	-	3.9	-	-
5 ACF-4	4.2	4.6		92
5 ACF-5	-	4.7	-	-
6 OR	2.4	2.9		82
6 PP-1	2.4	2.9		83
6 PPF-1	3.0	3.1		96
6 PP-2	-	3.4	-	-
6 PPF-2	-	2.9	-	-

TABLE 19 - SPLITTING TENSILE STRENGTH FOR DIFFERENT CONCRETE SAMPLES.

IDENTIFICATION	LOAD AT PROPORTIONAL LIMIT kN			MODULUS OF RUPTURE, STRENGTH MPa		
	7 d	28 d	91 d	7 d	28 d	91 d
1 AC	15.7	16.7	17.4	4.7	5.0	5.2
2 ACF	17.6	19.9	20.8	5.5	6.0	6.3
3 OR	16.3	17.5	17.9	4.9	5.3	5.4
4 ACF	15.7	16.3	17.3	4.7	5.0	5.5
6 OR	15.6	-	16.2	4.7	-	4.9
6 PP	16.1	16.1	17.5	4.8	4.8	5.3
6 PPF	16.8	17.9(2)	18.2	5.0	5.4(2)	5.5
5 ACF	16.5	17.4	18.1	5.8	6.2	6.4
5 ACF	15.5	15.2	17.4	5.6	5.9 *	5.6
5 ACF	-	-	16.8**	-	-	6.3 **

TABLE 20 - FLEXURAL TEST RESULTS FROM 100 X 100 X 400mm BEAMS AT ONE THIRD LOADING:

(2) Average of 2 beams

* Beam tested after 2 millions cycles of fatigue

** Beam tested after 10 millions cycles of fatigue and exposed for 1100 hours in salt fog.

AGE OF CONCRETE	% INCREASED AT PROPROTIONAL LIMIT		% INCREASED AT MODULUS OF RUPTURE	
	STEEL FIBERS	POLYPROPYLENE FIBERS	STEEL FIBERS	POLYPROPYLENE FIBERS
7 d	2.5	5.6	12.0	5.6
28 d	6.6	6.8	13.3	6.8
91 d	18.4	5.5	15.1	5.5

TABLE 21 - PERCENTAGE INCREASE OF FIBER REINFORCED CONCRETE OVER PLAIN CONCRETE.

No.	A) ESTIMATED LOAD AT RUPTURE kN	APPLIED LOAD % of A)	NUMBER OF CYCLES	REMARKS
6 OR	16,0	60.6	54 850	FAILURE
6 OR	16,0	60.6	150 000	FAILURE
6 OR	16.0	60,6	165 800	FAILURE
6 PPF	17,9	58,6	370 360	FAILURE
5 ACF (4)	16,4	91,5	77 000	FAILURE
5 ACF (4)	16,4	59,1	2 000 000	CRACKING *
5 ACF (4)	16,4	59,1	10 000 000	CRACKING *

TABLE 22 - FATIGUE RESISTANCE OF PLAIN AND FIBER REINFORCED CONCRETE AT 28 DAYS.

* Cracking occured at ~ 1,500,000 cycles on one quarter of the height.

TYPE OF CONCRETE	28 DAYS		91 DAYS	
	1st TEST	2nd TEST	AVERAGE	STANDARD DEVIATION
PLAIN	8/9**	9/10	17/19	24/20
POLYPROPYLENE	103/111	11/18	33/39	54/43
STEEL FIBER	39/147	16/94	55/130	83/59

TABLE 23 - IMPACT RESISTANCE OF PLAIN AND FIBER REINFORCED CONCRETE.

* First visible crack.

** Ultimate failure.

ANNEXES REPORT

A-1 The influence of fibre addition on concrete microstructure

A-2 Highway Inspection April 16th, 1985

A-3 Hardened concrete air content

A-4 Inspection of Highway A-15 on July 26, 1985

A-5 Joint Movement

ANNEX 1

The influence of fibre addition on concrete microstructure

The mercury intrusion curve was plotted on two representative samples for each of the three types of concrete used during the making of the experimental slabs.

Figure 1-A shows that the addition of steel or polypropylene fibres does not modify significantly the mercury intrusion curve compared to plain concrete. However, the delivered concrete shows a macroporosity (pores between 0,1 and 1,0) representing 25 to 35% of the total volume which is rather unusual for concrete of such strength.

The hypothesis of such a macroporosity may have been caused by the action of the water reducer admixture used by the concrete supplier. This macroporosity could reduce durability if the air bubble spacing is not adequate.

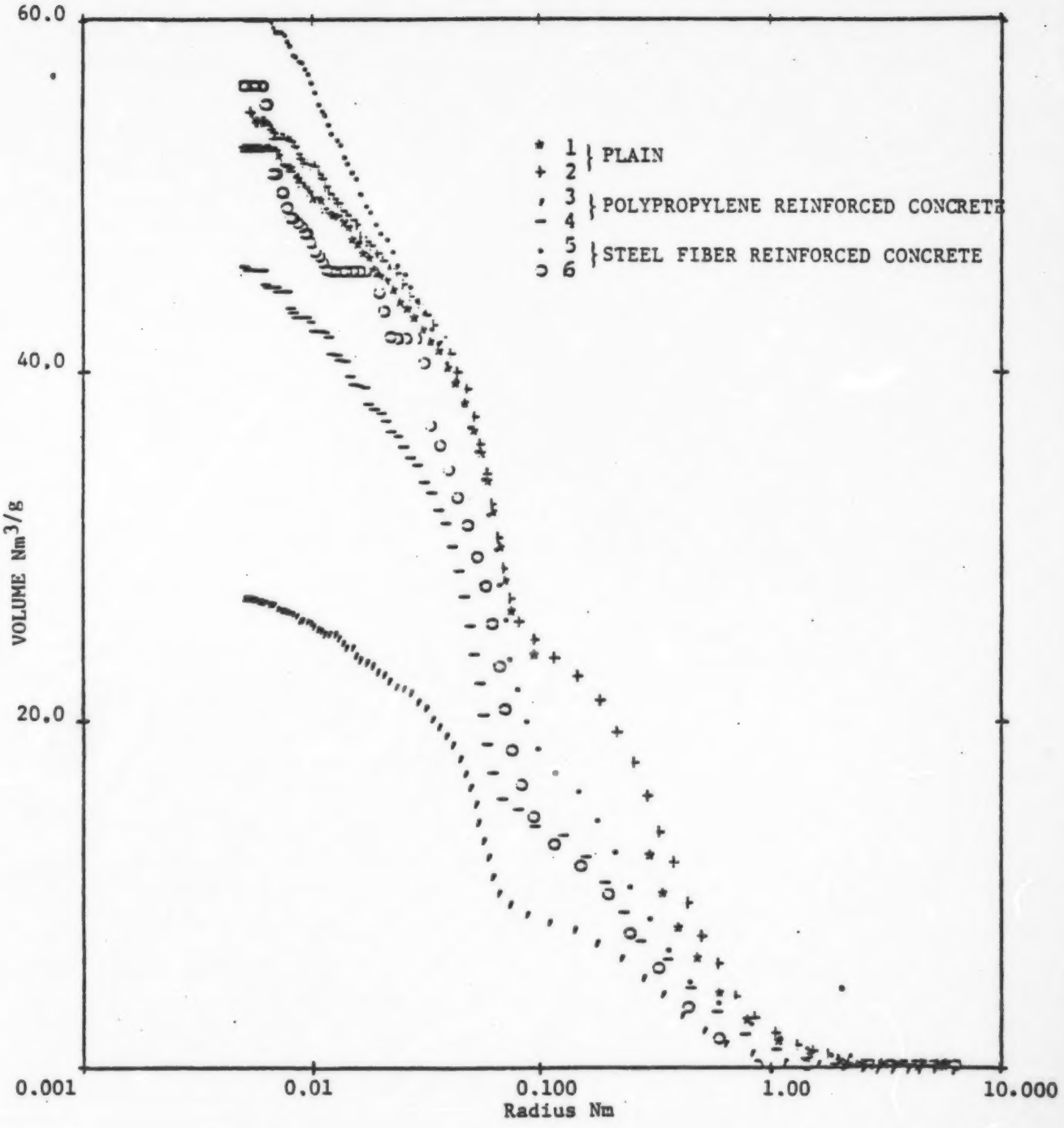


FIGURE 1-A POROSIMETRIC CURVE OF 6 SAMPLES OF CONCRETE.

ANNEX 2

Highway Inspection

April 16th, 1985

On April 16th, 1985, the experimental slabs containing steel and polypropylene fibres were inspected by the authors accompanied by M.T.Q. engineers (Napierville region) MM. André Hamelin and Gildard Lanteigne.

The following observations were made:

1°) The steel fibres exposed to the surface were corroded. We have observed a similar behaviour when samples were exposed in the salt fog cabinet.

2°) From the presence of the corroded fibres to the surface, we can assume the homogeneity of the dispersion of fibres. In the experimental slabs poured on the first day, we observed large rust stains where fibres balled, however, on the slabs poured on the third day, the corroded fibres are evenly dispersed throughout the surface.

3°) Generally, the sawed joints made in the slabs containing steel fibres has not worked as intended. These joints did not open, and the caulking material remained intact. This observation had already been confirmed by the readings of the joint meters during the winter months.

4°) The sawed control joints opened during winter, but because of the presence of dowels through the joints, there was no rocking of the slabs.

5°) For polypropylene reinforced concrete slabs, the control joints opened during winter, and after the first winter, there is rocking of the adjacent slabs. In the absence of dowels in the control sawed joint, polypropylene fibres are not capable of securing the joint; there was rocking of the slab.

6°) In the 60 feet long slab, the presence of steel welded wire mesh did not prevent transversal cracking. This phenomenon was not observed for the steel fibre reinforced concrete slabs, even though the sawed joints did not open.

CONCLUSION

The steel fibre reinforced concretes poured on the third day were very homogeneous.

There is no need for a control joint at 20 feet, but a joint spacing of 60 feet with dowels should be sufficient. However, great care should be taken in the caulking application, because the linear variation will be three times greater.

The surface finish leaves much to be desired because no vibrating screen was used. The wavy surface increases the fatigue of concrete and should consist in a very severe test for the experimental slabs.

After the first winter, the steel fibre reinforced concrete slabs (even the ones poured on the first day) had behaved very satisfactorily. The use of polypropylene fibres as reinforcement in highway slabs is obviously without any interest.

ANNEX 3

Hardened concrete air content

Figure 2-A shows the air content and bubble spacing of hardened concrete.

The freeze-thaw and scaling durability characteristics were found very satisfactory for the plain concrete delivered at the job site.

The addition of steel fibres and superplasticizers at the batch plant, increased both the bubble size and spacing. The values of 342 or 327 µm is not catastrophic, since the concrete is not always saturated in nature when it is submitted to freeze-thaw cycles combined with de-icing salts, but this limit should not be exceeded.

The addition of polypropylene fibres at the jobsite combined with the addition of superplasticizer has not only broken down the air bubble network but resulted in the entrainment of large air bubbles which represents little interest for durability.

The latest confirms without any doubt that steel or polypropylene fibres must be added at the batch plant. Moreover, the use of superplasticizer in road works should be studied thoroughly, particularly the influence of different types of superplasticizer on different brands of cement.

	NUMBER OF SECTIONS	TOTAL AIR ENTRAINMENT %	SPECIFIC AREA MM^{-1}	SPACING FACTOR	
				GROSS µm	WITHOUT LARGE BUBBLES µm
PLAIN CONCRETE	3	8.2	15.4	193	128
WITH STEEL	3	7.7	11.4	342	327
WITH POLYPROPYLENE	3	5.8	10	484	375

FIGURE 2-A - SIZE AND SPACING FACTOR OF ENTRAINED AIR IN HARDENED CONCRETE.

ANNEX 4

Inspection of Highway A-15

on July 26, 1985

The joint meters were removed on this day, and we took advantage of the road block to one lane traffic to make a visual inspection of cracks. Also, we have surveyed the cracks in adjacent slabs 17 to 34 inclusively which occured after the repair work. Unfortunately, the crack survey outside the experimental project was not done before the works.

Figure A 4.1 shows a detailed plan of slabs 17 to 34 indicating the repairs and the cracking pattern and a regional map showing the exact location of the experimental project.

The following observations were made:

1) The fiber reinforced slabs did not crack during the first 9 months. Nevertheless, the polypropylene fiber concrete slab rocked because of some warping occured at early age and no dowels were used at the control joints. The warping was not caused by the use of polypropylene fibers.

2) The behaviour of steel fiber reinforced concrete slabs confirms the observations made last April 16th. The control joints which are usually 5 m apart can be spaced 15 to 20 m.

3) The experimental slab #30 is the only one which cracked amongst all the dowelled control joint plain concrete slab.

4) The number of cracks developped within only 9 months in the adjacent slabs outside the experimental project is rather surprising. The rate of cracking can only be explained by the bad quality of the subgrade.

CONCLUSIONS

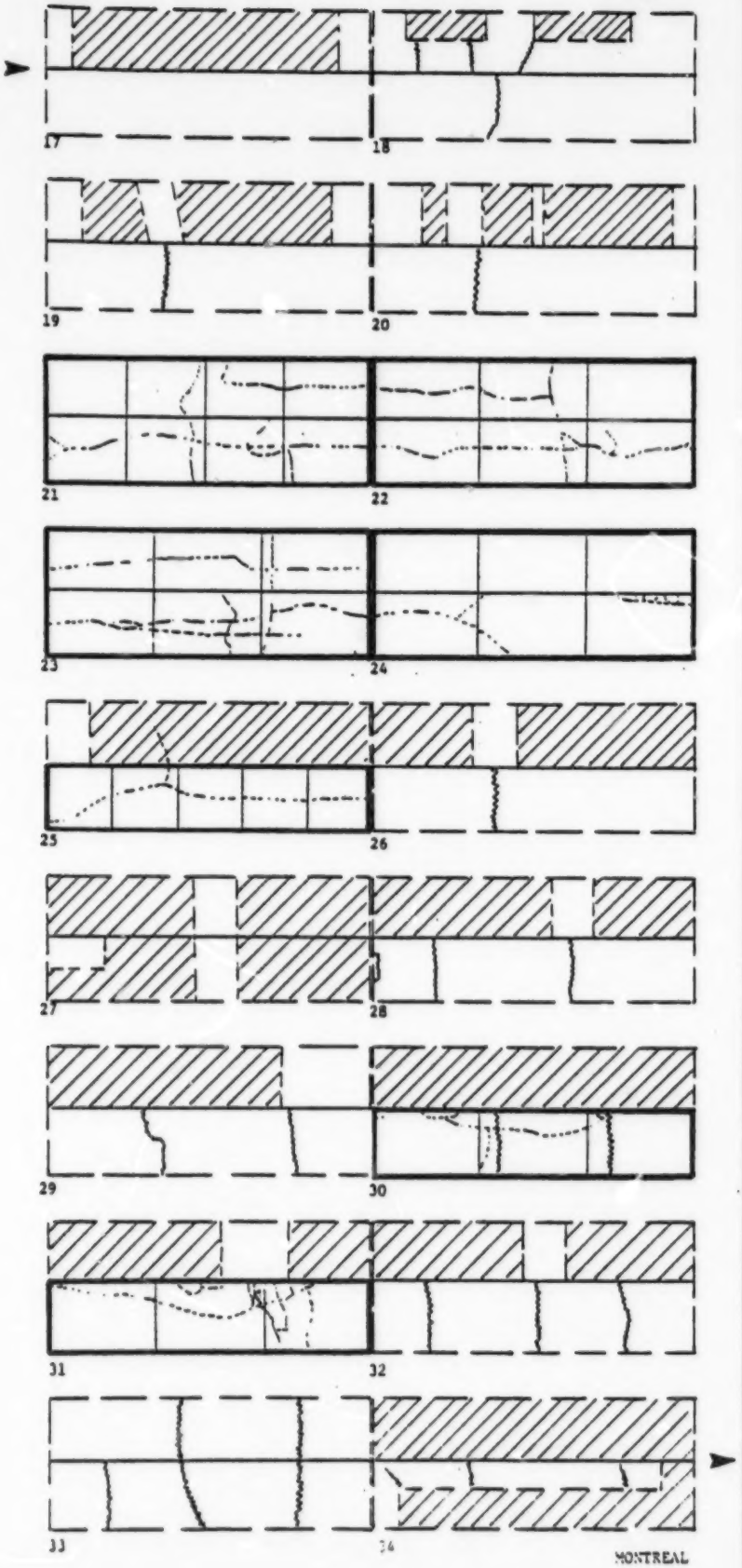
1) After 9 months of service, the steel fibres reinforced concrete slabs did not crack, where 90% of wiremesh reinforced concrete slabs cracked.

2) There is not sufficient strength developped by the polypropylene fibres to hold tightly the slab on either side of the control joint and some rocking was observed.

3) Because none of the sawed joint has openned in steel fibre reinforced concrete, is is useless to provide control joints every 5 to 6 m.

TYPE OF SLABS	NUMBER OF SLABS INSPECTED	CRACKED AFTER 9 MONTHS	% OF CRACKED SLABS
EXPERIMENTAL			
Steel fibres	6	0	0
Polypropylene fibres	1	0	0
Plain concrete	4	1	25
OTHERS			
Complete repairs	10	9	90
Partial repairs	13	2	15
Not repaired	2	0	0

Table A 4.1 - Slab state of cracking comprised between no 17 to 34.



EXPERIMENTAL SLAB

SLAB NOT INCLUDED IN EXPERIMENTAL PROJECT

SURFACE NOT REPAIRED

TRANSVERSE JOINT

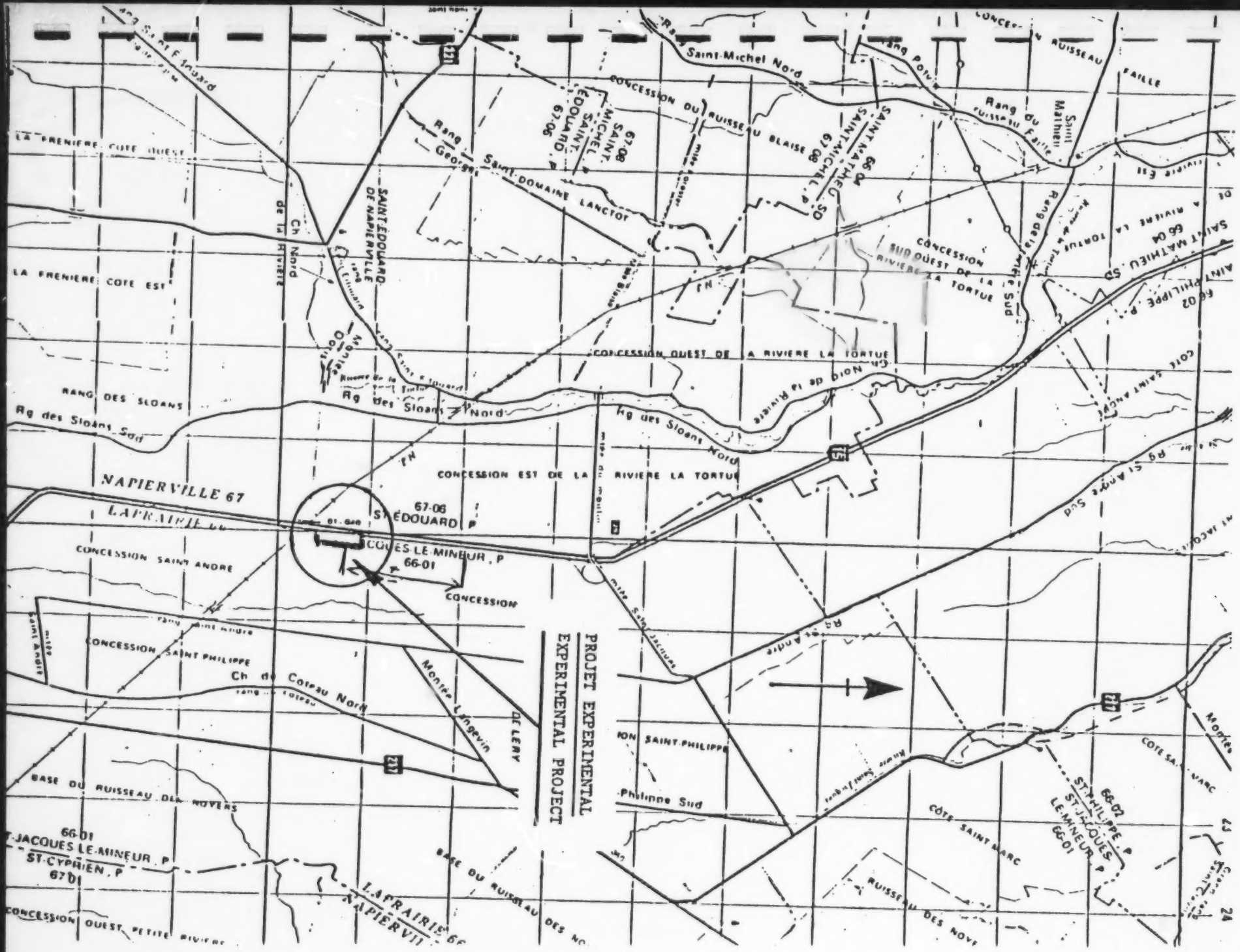
LONGITUDINAL JOINT

CRACK BEFORE REPAIRS

CRACKS AFTER REPAIRS (9 months)

TRAFFIC DIRECTION

22 SLAB IDENTIFICATION


PROJET EXPERIMENTAL
EXPERIMENTAL PROJECT
NAPIERVILLE 67
LAFRAIRIE
67-06
ST-ÉDOUARD P
COTES-LE-MINEUR P
66-01
ST-JACQUES-LE-MINEUR P
66-01
ST-CYPRIEN P
67-01
ST-PHILIPPE P
66-02
CONCESSION EST DE LA RIVIERE LA TORTUE
CONCESSION OUEST DE LA RIVIERE LA TORTUE
CONCESSION SAINT ANDRE
CONCESSION SAINT PHILIPPE
Rang Saint-Michel Nord
Rang des Sloans Nord
Rang des Sloans Sud
Ch de Coteau Nord
Ch Nord de la Rivière
Ch Côte Nord
Ch de la Rivière
Rang Saint-Georges
Rang du Ruisseau
Rang du Fossé
Rang Pointe
Saint-Edouard de Napierville
Saint-Domaine Lanctot
Concession du Ruisseau Blaise
Saint-Michel
Saint-Mathieu
Saint-Mathieu-Sud
Saint-Philippe
Côte Saint-André
Côte Saint-Marc
Montée Langevin
Montée de Leary
Base du Ruisseau des Noyers
Ruisseau des Noyers
Philippe Sud
Concession Ouest Petite Rivière
Concession Sud Ouest de la Rivière la Tortue
La Frenière Côte Ouest
La Frenière Côte Est
Faille
Ruisseau
Rang Saint-Michel Nord
Rang des Sloans Nord
Rang des Sloans Sud
Rang Saint-André Sud
Rang de la Pointe
Rang du Ruisseau
Rang du Fossé
Concession
Côte Saint-André
Côte Saint-Marc
Montée
Ruisseau des Noyers
Base du Ruisseau des Noyers
Concession Ouest Petite Rivière
Concession Saint Philippe
Concession Saint André
Concession Est de la Rivière la Tortue
Concession Ouest de la Rivière la Tortue
Concession Sud Ouest de la Rivière la Tortue
Saint-Mathieu-Sud
Saint-Philippe
Saint-Jacques
Saint-Edouard
Saint-Michel
Saint-Mathieu
Saint-Georges
Saint-Domaine Lanctot
Saint-Edouard de Napierville
Ch Nord de la Rivière
Ch de la Rivière
Ch Côte Nord
Ch de Coteau Nord
Rang Saint-Georges
Rang du Ruisseau
Rang du Fossé
Rang Pointe
Faille
Ruisseau
Côte Saint-André
Côte Saint-Marc
Montée Langevin
Montée de Leary
Base du Ruisseau des Noyers
Ruisseau des Noyers
Philippe Sud
Concession Ouest Petite Rivière
Concession Saint Philippe
Concession Saint André
Concession Est de la Rivière la Tortue
Concession Ouest de la Rivière la Tortue
Concession Sud Ouest de la Rivière la Tortue
La Frenière Côte Ouest
La Frenière Côte Est
Napierville 67
Lafrairie
St-Édouard P
Cotes-le-Mineur P
St-Jacques-le-Mineur P
St-Cyprien P
St-Philippe P
67-06
66-01
66-02
67-01
67-08
66-04
66-03
24
43

ANNEX 5

JOINT MOVEMENT

Figure 1 shows the positionning of the joint meters type JO-FO where one was bridging a construction joint and 4 others were set across a control joint. The joint meters were able to register a maximum displacement of $\pm$ 6 mm.

From November 23, 1984 to July 26, 1985, sixteen readings were registered. During this period, the ambiant temperature varied from -20°C January 16 to + 26°C on July 26. The concrete temperature measured by the joint meter varied from -12.9°C on January 16 to +25.2°C on July 10 and 26. The latest are the average temperature readings from the 5 joint meters.

Table A 5.1 shows the readings for that period and are reported graphically on figure A 5.2.

DISCUSSION

COMPARISON OF AMBIANT AND CONCRETE TEMPERATURES

From table A 5.2, it can be seen that the concrete slab temperatures are 5°C higher than ambiant temperatures during the winter months but there is a thermal equilibrium during the warmer months.

CONSTRUCTION JOINT MOVEMENT

The joint meter bridging the construction joint between two steel fibre reinforced concrete slabs failed between April 16 and 30, 1985 when the concrete temperature raised significantly. The 6 mm maximum permissible displacement was

exceeded when high concrete temperature caused excessive expansion of the slab. Figure A 5.3 shows the variations of the joint openning as a function of the slab temperature measured with the joint meter. The graph shows a remarquable linear relationship between the temperature and the joint movement, thus, the linear expansion relation of the concrete to the temperature was well followed. By extrapolation from the graph, it can be concluded that the maximum slab temperature rose to 27°C between April 16 to 30, 1985. The warmest ambiant temperature during this period was 23°C registered on April 30 in Sherbrooke and Dorval weather station.

STEEL FIBRES REINFORCED CONCRETE CONTROL JOINTS

There is no significant movement in the second of the two joints before June 26, when some slight erratic movements were detected. The visual inspection shows that there is no cracking through the joint. Therefore it was useless to saw this control joint because it did not fulfil its objective.

The first of the two joints seemed to have closed slightly on the first few days of March to open up later on, and came to its initial position. The measured range was so weak (0.99 mm on March 19 and May 14) that it is believe this joint was also useless to saw.

PLAIN CONCRETE SLAB CONTROL JOINT

Table A 5.1 and figure A 5.2 show the openning of the joints during the winter months. The slab with the joint meter cracked between May 14 and 29, and a second crack appeared beween June 11 to 26, so that the readings after May 14 are meaningless. The advent of those two cracks is not attributable to a thermal phenemenon, because the concrete temperature did not exceeded 15°C, but it may have been caused by a weak subgrage.

CONCLUSION

1) During the winter months it was noticed that the concrete slab temperature always exceeded the ambiant temperature by $5^{o}C$. During the summer months the concrete temperature is in equilibrium with ambiant air temperature.

2) For the plain concrete, the width of the control joint varies as a function of the temperature.

3) It is useless to provide control joint for steel fibre reinforced concrete; however, dowels should be provided at construction joints to assure the slab alignment, and load transfer.

4) The construction joint width varies linearly as a function of temperature and slab length.

	JOINT METER MOVEMENT mm					TEMPERATURE °C	
	STEEL FIBRE CONCRETE SLAB		PLAIN CONCRETE				
DATE	CONSTRUCTION	CONTROL				CONCRETE	AMBIANT
84-11-23	0	0	0	0	0	1.1	-4
84-12-18	-0.22	-0.07	-0.02	-0.26	-0.28	2.3	-1
85-01-16	+2.94	-0.15	-0.12	+1.82	+0.89	-12.9	-20
01-29	+2.41	+0.49	+0.48	+1.90	+0.97	- 8.1	-14
02-12	+1.73	-0.05	-0.03	+1.25	+0.50	- 6.6	-10
02-26	+0.13	-0.20	0	+0.36	+0.33	- 2.3	- 6
03-19	+0.03	-0.98	+0,08	+1.41	+0.91	- 5.9	-10
04-16	-3.24	-0.55	-0.08	0	-0.17	15.3	18
04-30	(3)	-0,45	+0,12		+0,35	12.0	12
05-14		-0,99	-0.43	+0.46	-0.12	12.6	12
05-29		-0.55	-0.02	+0.50*	+0.36*	20.3	20
06-11		-0,45	+0,12	+0.76*	+0.33*	16.3	15
06-26		-0.02	-1,04	+1.32**	+0,83**	16.2	16
07-10		-0,05	+0.56	+0,85**	+0.55**	25.2	21
07-23		0	+0,59	+1.01**	+0,68**	24,2	24
07-26		-0.29	+0,31	+0.60**	+0.25**	25.2	26

(1) + = Joint opens
- = Joint closes

(2) Concrete temperature = temperature measured by joint meter

(3) Joint meter failed

* Cracking in the center of the slab

** Second crack occured in the slab.

TABLE A5.1: READINGS OF JOINT METERS MOVEMENT BETWEEN NOVEMBER 23, 1984 to JULY 26, 1985

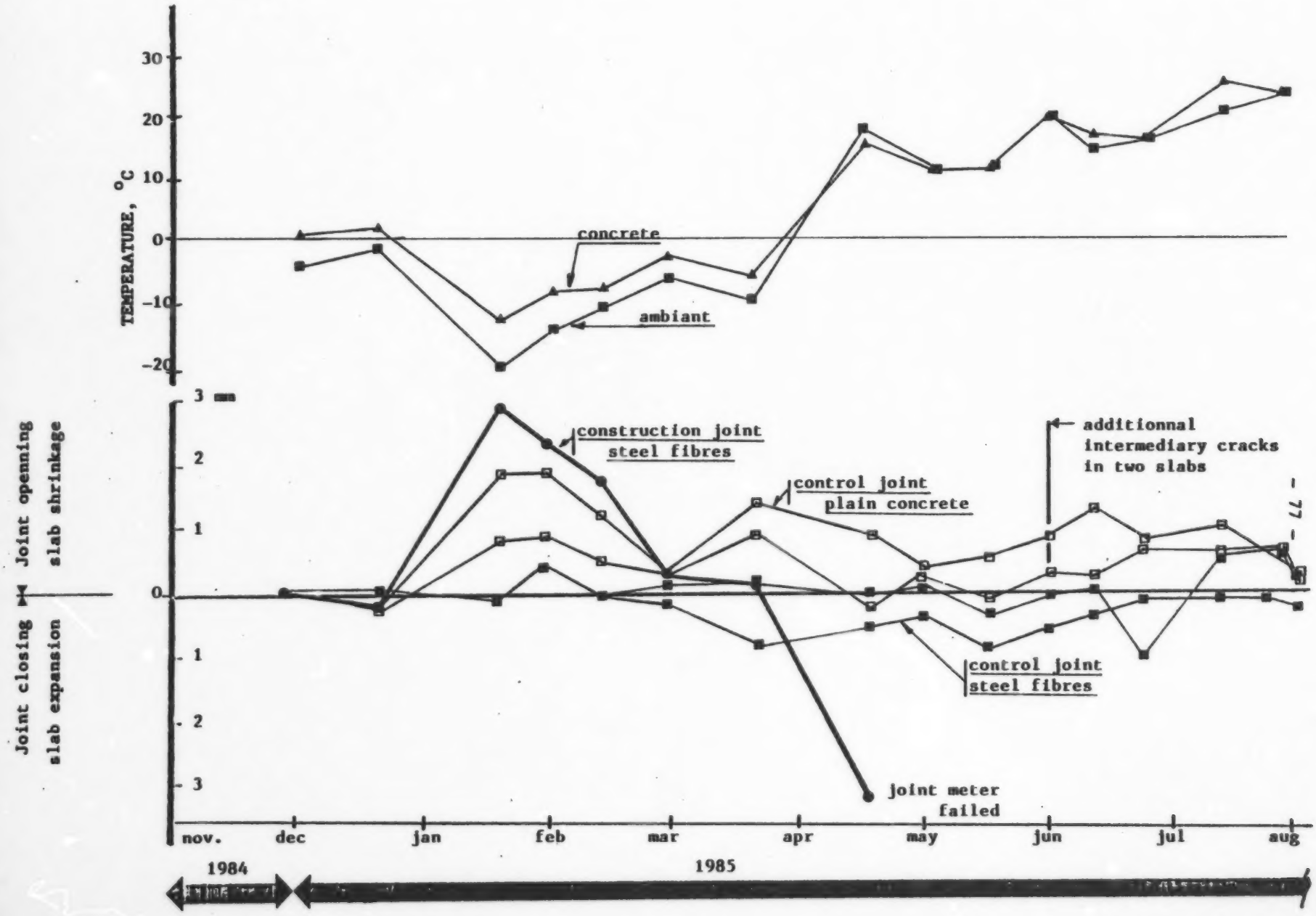


Figure A 5.2 - JOINT MOVEMENT AND TEMPERATURES

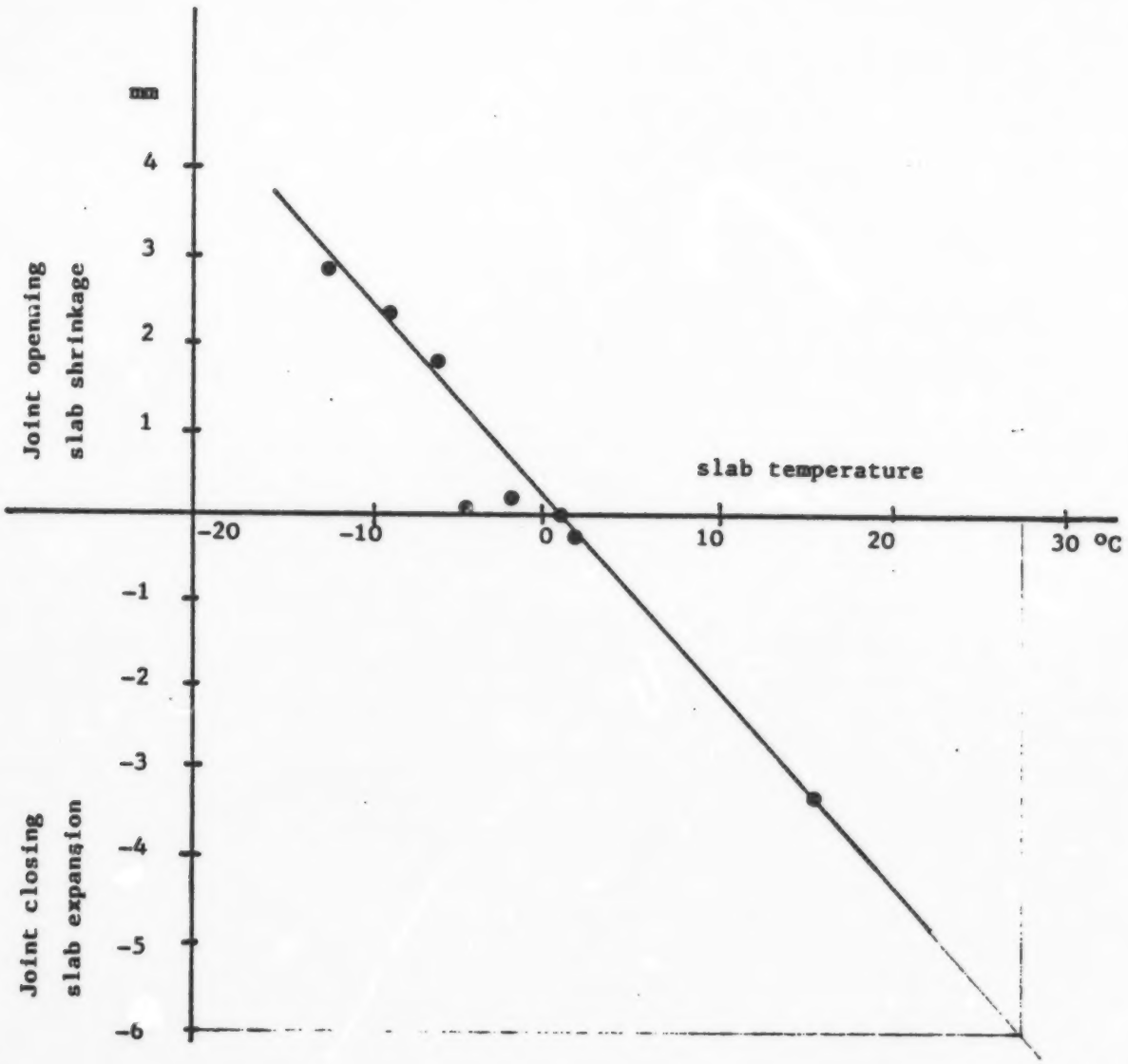


Figure A 5.3 - Joint movement as a function to the concrete slab temperature